MODELING STUDIES OF THE RESPONSE OF WEAPON FOUNDATIONS IN SOILS

PHASE I FINAL REPORT

GALE E. NEVILL, JR.

JUNE 1963

Contract No. DA-23-072-ORD-1375
Task Order No. 13

DA Project Number Within
Army Materiel Command
1A025001A622 Formerly
DA Project Number
1A650212D622 and 5B98-09-004

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS

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1. INTRODUCTION

The designer faced with the problem of tomorrow's weapons has many competing factors to consider. These factors include the need for simplicity, reliability, light weight, ruggedness, accuracy, fire power, minimum cost, minimum time for emplacement and deplacement, and maximum mobility. Generally speaking, it will be impossible to provide all desirable qualities since many are mutually exclusive and any practical weapon will be a compromise among competing requirements.

At present, the state of the art allows for design of the mechanical portions of the weapon with a high degree of refinement. This does not mean that all mechanically desirable features can be achieved but rather that the necessary knowledge and analytical techniques are available so that an optimum compromise may be defined and reached. That portion of the problem involving terrain platforms is quite different, for the present knowledge of their reactions is inadequate to allow reliable prediction of displacements of various geometries of foundations subjected to various impulsive loads—a factor which is one of the most serious limiting the design of future weapon footings or mounts, particularly from the point of view of firing stability.

The functional relationships or behavioral characteristics of the terrain platforms which are, of course, soils are much more complex than those for most other common engineering materials such as metals, fluids, etc. In fact, soils often combine inertial, elastic, plastic, viscous, and frictional characteristics, with very nonlinear relationships among them. Further, the presence of layering with depth, widely different moisture contents, etc., leads to a wide variation in mechanical properties of soils and thus makes the general prediction of soil behavior extremely difficult. Fortunately, however, soils can be broadly classified as to their mechanical behavior and therefore it will probably not be necessary to treat the entire range of properties at one time, but will be sufficient to develop the necessary relationships for each soil class separately. Even this approach, however, is not simple.

Three possible approaches to the development of necessary functional relationships among weapon and soil parameters may be considered. The first of these will be called the analytical approach and is typified by the mathematical development of equations for system behavior. The advantages of this approach are the relatively low cost and broad range of application of resulting functional relationships. In this particular application, however, the disadvantages are extremely serious. The mathematical difficulty in describing the weapon foundation geometries and in including the entire range of soil behavioral characteristics is quite formidable and would lead to extremely complex equations to be solved, _if_ such could be formulated. The basic level of understanding of the interrelationships among various parameters is so inadequate, however, that it is not considered feasible at present to formulate these equations in the necessary generality and the level of knowledge is also insufficient to allow useful simplifications and approximations to be made. A purely analytical approach is therefore not considered feasible.

A second approach would be the use of full-scale testing to develop the necessary quantitative data and functional relationships. The advantage of full-scale testing is that the results obtained can be used with a high level of confidence. The disadvantages are most serious, however. One disadvantage is the difficulty in obtaining the desired variation of weapon parameters to include ranges for possible future weapons. The next disadvantage involves the difficulties in instrumentation of full-scale tests. Both of these two difficuties could be overcome with sufficient effort. However, there lies the most serious drawback of all, high cost. Full-scale testing is considered more promising than strictly analytical efforts, but is recognized as being extremely expensive.

The third approach to the problem involves the use of models to obtain the necessary quantitative information to allow for the development of functional relationships. The use of models solves most of the problems of full-scale testing and includes ready achievement of the necessary ranges of parameters, relative ease of instrumentation, and much reduced cost. The one serious problem to be overcome involves the necessity for developing and verifying the modeling techniques so that model test results can be confidently extended to full-scale behavior. This third approach, the use of models together with a limited quantity of full-scale testing for technique verification and the use of analysis wherever possible, is believed both desirable and feasible. Before this most promising approach could be effectively utilized, however, it was necessary to develop and verify appropriate modeling techniques.

This report presents the results of the first phase of a three-phase effort which is designed to lead to a handbook for the foundation aspects of the weapon design problem. Thus, the end product of the overall program is to be a weapon foundation design handbook which will allow the designer to make optimum decisions and compromises during the foundation design phases of his work.

The overall approach to this problem chosen as the most promising involves the use of models of foundation elements to generate the necessary quantity of experimental data throughout the range of weapon and soil parameters. This first phase of the overall program has involved four primary steps. These steps include:

1. A dimensional analysis and similitude study to determine the most general requirements for successful simulation

2. Development and verification of modeling techniques and establishment of accuracy levels attainable

3. The determination of those properties of various soils and those weapon parameters which are significant to the problem

4. The selection and development of means for measuring the various significant soil properties

In summary, this report describes a research effort which has brought the described approach to the point of verified feasibility. The next phase of the overall effort will involve the detailed design, construction, checkout, and use of a model test facility and the final phase of the overall effort will involve completion of accumulation of experimental data, the analysis of this data, the development of nomographs, functional relationships, etc., and the preparation of a weapon foundation design handbook.

2. SIMILITUDE ANALYSIS

Introduction

In the modeling of physical phenomena which are well understood and which may be accurately described mathematically, similitude or modeling requirements may be obtained readily from examination of the differential equations describing the phenomena. In this case, there is little problem as to the possibility of omissions of significant effects or the inclusion of extraneous ones. Unfortunately, the present problem, involving the response of soils to impulsive loadings, is not well understood and certainly has not been adequately described mathematically. The selection of the set of significant parameters in this problem, therefore, is quite critical.

The inclusion of extraneous or unimportant parameters leads to modeling requirements which are unnecessarily complex and perhaps impossible to achieve. Alternatively, the omission of significant parameters may introduce serious errors and render results unusable or meaningless. The approach taken here has been to provide a similitude analysis which is quite complete, and then to utilize experiments to determine which parameters may be neglected and the effects of inexact simulation.

Selection of Significant Parameters

Preliminary studies of the overall weapon foundation problem indicated that the significant parameters could be divided into the following groups:

(1) Weapon and loading
(2) Soil inertial
(3) Soil frictional
(4) Soil elastic
(5) Soil plastic compaction (time independent volume change)
(6) Soil plastic shear (time independent shear)
(7) Soil viscous compaction (time dependent volume change)
(8) Soil viscous shear (time dependent shear)
(9) Foundation response

These groups are discussed individually below.

Group 1: Weapon and Loading Parameters. The load applied by the weapon foundation to the soil, i. e., the force and stress acting between the foundation element and the soil is not an independent parameter. This force is a function of both weapon and soil characteristics; for example, if the weapon were fired in free space, there would be no force exerted on the foundation elements and the force acting, if the foundation were set in concrete, would certainly be different from that if the foundation were in a weak soil. Obviously, the problem cannot be uncoupled at the foundation-soil interface. Since it is not possible to specify the foundation load independently, other characteristics of the weapon must be included.

Observations of the rod-pull force-time histories for various types of soils indicate that the weapon designer has been successful in making this force-time history essentially independent of the soil properties. It is considered appropriate, therefore, to uncouple the problem at this point.

Another point is the possibility of considering only an initial velocity of the mass of the non-recoiling weapon parts, i. e., of the carriage, trails, anchoring elements, etc. This may be done if the duration of rod-pull load is sufficiently small compared with weapon overall response time or if the weapon anchor standoff from the soil is sufficiently large. In this case, an initial velocity would be specified rather than the exact rod-pull force-time history.

It is considered probable that the weapon mass may be considered rigid as compared with the soil; this may not be the case for all combinations of weapon configuration and soils, however. If this mass cannot be considered rigid, then appropriate scaling of its stiffness would also have to be included.

The weapon anchor geometry may be described by the specification of a characteristic length for the anchor, together with various non-dimensional length ratios and angles.

Since the response to repeated impulsive loads is here considered, it is also necessary to include identification of the various impulsive loadings in sequence. If the series of impulses is identical, a number denoting the chronological placement of the impulses is sufficient. For non-identical impulses, however, it will be necessary to include specification of the chronological number and of the detailed characteristics of each individual impulse.

Based on the above considerations, the following list of weapon and loading parameters has been selected:

M	Mass of non-recoiling weapon parts
F	Characteristic rod-pull force
T	Characteristic rod-pull time
f(t/T)	Non-dimensional rod-pull force-time history function, where t is real time
V	Initial velocity of non-recoiling mass M (to replace F, T, and f (t/T) under conditions discussed above)
L	Characteristic length of foundation or anchor element
l_i	Non-dimensional length ratios necessary to describe anchor geometry
θ_i	Angles necessary to describe anchor geometry
n	Impulse number, i. e., chronological identification number
K	Weapon characteristic spring constant representing flexibility of connection between non-recoiling mass and foundation elements.

<u>Group 2: Soil Inertial Properties.</u> The soil resistance to acceleration, or its inertial properties, may be described by the specification of a characteristic density ρ and by the appropriate functional relationships describing the variation in density with compaction, shear flow, etc. In this regard, it is considered satisfactory to treat volume changes or

compaction as equivalent to density changes and to consider, therefore, only the functional relationships between volume changes and other parameters .

The initial soil mass density ρ is therefore listed as the only parameter necessary to describe soil inertial properties.

<u>Group 3: Soil Frictional Characteristics.</u> Most soils exhibit frictional characteristics in the nature of a coefficient of friction, or an angle of friction which expresses a functional relationship between the shear stress at failure and the accompanying normal stress on the plane of failure. It is considered sufficient to assume this relationship to be linear for all soils; hence, a single constant ϕ , the angle of friction, may be used to describe this property. Expressed mathematically, this means

$$s = c + p \tan \phi$$

where s = shear stress at failure, p = normal stress, and c = constant.

<u>Group 4: Soil Elastic Characteristics.</u> Soil elastic properties, i. e., linear reversible stress strain behavior, will probably be relatively unimportant on the first loading cycle but may become significant after a number of impulses at which time appreciable compaction has taken place. It is therefore probably not adequate to specify the in situ soil elastic properties, but rather it will be necessary to specify values after certain amounts of compaction, etc., and perhaps to specify the functional

relationships describing elastic behavior as a function of shear deformation, compaction, etc.

The elastic behavior of a material is completely defined if only two parameters of the following four are known: Young's modulus, shear modulus, bulk modulus, and Poisson's ratio. Here, the bulk modulus B and the shear modulus G are selected. Considerations of functional relationships will be discussed in the next two sections covering the time independent compaction and time independent shear in more general terms.

Group 5: Soil Time Independent Volume Changes or Compaction. In this category are considered changes in volume which are not dependent on load time duration, except as they might be influenced by deformation rate. In the most general case, compaction would be a function of all stresses and of the strain history of the soil. It is not considered necessary, however, to describe the compaction behavior in this detail. In this problem, it is considered satisfactory to describe the time independent compaction through description of the relationship of volume change or compaction versus uni-axial or uniform tri-axial compression. In this case, the elastic modulus would be included as the initial slope of the curve upon first loading or as a representative slope for unloading or reloading on subsequent cycles. Further, it is considered probable that strain and deformation rate effects can be neglected so far as the difference in their influence on model and prototype is concerned, since the rates will vary at most by one order of magnitude.

Considering soil void ratio as the ratio of volume other than the basic lattice to basic lattice volume, changes in void ratio would be an appropriate measure of this parameter. Since there is considerable information available on void ratios and on their changes due to stress, it may be advantageous to use void ratio rather than compaction.

At present, it is considered appropriate to describe the soil time independent compaction characteristics in terms of a single dimensional characteristic constant B, the bulk modulus, and the non-dimensional quantities b_i necessary to define the remainder of the compaction-stress curve for uniform stress.

<u>Group 6: Soil Time Independent Shear Characteristics.</u> The characteristics considered here are those associated with the time independent resistance to shear considered independently of any normal forces. This parameter is then associated with cohesion of the soil and not with frictional characteristics which were discussed in Group 3.

Here, as in Group 5, it is considered appropriate to neglect rate effects and to consider only the curve of shear stress versus shear strain of the material. The elastic shear modulus G would be included as either the initial slope of this curve or as the initial slope of the unloading/reloading curve after some number of impulsive loads. The shear strength of the material may be quite dependent on the compaction taking place, however, and it is possible that this functional dependence would have to be described in order to fully define the time independent shear characteristics.

The time independent shear characteristics will be defined in terms of a characteristic dimensional constant G (the elastic shear modulus) and the number of non-dimensional parameters g_i necessary to define the shear stress versus shear strain curve.

Group 7: Soil Time Dependent Compaction. Whereas dry granular soils do not exhibit appreciable time dependent deformation, it is expected that other soils, particularly wet clays, would exhibit significant time dependent deformation.

This characteristic is expected to be most strongly influenced by the permeability of the soil and by the dependence of permeability on compaction and shear flow. Although, for clays in particular, other mechanisms would be involved, it is considered satisfactory at this time to characterize soil time dependent compaction by a single dimensional parameter C, which relates the time rate of change of volume due to a uniform compressive stress which is applied in such a way that the liquid content of the specimen is able to flow out of the specimen.

Group 8: Soil Time Dependent Shear. As with Group 7, dry granular soils would probably not exhibit deformation of this nature whereas cohesive soils with high moisture contents would. Although possibly an over-simplification, at this time it is considered sufficient to express the soil viscous or time-dependent shear characteristics in terms of a single linear viscosity coefficient μ relating shear strain rate to shear stress.

Group 9: Response Parameter. In this program, the soil cumulative permanent displacement Z is the most important dependent parameter. The individual displacements z for each impulsive load might also be important, however. Since displacements after a number of impulsive loads are of interest, it is necessary to associate the displacement parameters with a corresponding impulse number. Here, the response parameters considered are Z(n), the cumulative permanent anchor displacement, and z(n), the individual anchor displacement where n is the chronological impulse number.

Thus far, no size or shape has been specified for the soil. If such are necessary, they can be accomplished by specification of additional non-dimensional ratios l_i of length compared with the characteristic weapon foundation length L, and additional angles θ_i . Also, if the soil conditions are sufficiently inhomogeneous that more than one set of properties must be specified, these can be defined in terms of non-dimensional ratios to the properties listed for one soil. For brevity, these latter ratios will not be included specifically in the following, since the resulting similitude requirements would simply be equality of these ratios in model and prototype systems.

As described in the preceding paragraphs, the following parameters have been chosen as those significant and necessary in the modeling of the problem at hand.

Weapon and Load Parameters		Dimension
M	Mass of non-recoiling weapon parts	$FL^{-1}T^2$
F	Characteristic rod-pull force	F
T	Characteristic rod-pull time	T
$f(t/T)$	Non-dimensional rod-pull force-time history function, where t is real time	----
V	Initial velocity of non-recoiling mass M (to be used in place of F, T, and f(t/T) under conditions discussed above)	LT^{-1}
L	Characteristic length of foundation or anchor element	L
l_i	Non-dimensional length ratios necessary to describe anchor geometry and soil	----
θ_i	Angles necessary to describe anchor geometry and soil	----
n	Impulse number, i. e., chronological identification number	----
K	Weapon characteristic spring constant representing flexibility of connections between non-recoiling mass and foundation elements	FL^{-1}

Soil Parameters		
ρ	Soil initial mass density	$FL^{-4}T^2$
ϕ	Soil angle of friction	----

B	Soil bulk modulus	FL^{-2}
b_i	Non-dimensional parameters necessary to define stress-compaction curve	----
G	Soil shear modulus	FL^{-2}
g_i	Non-dimensional parameters necessary to define shear stress versus shear strain curve	----
C	Soil viscous compaction parameter	$FL^{-2}T$
μ	Soil viscous shear coefficient	$FL^{-2}T$

Foundation Response

Z(n)	Cumulative permanent anchor displacement after nth impulsive load	L
z(n)	Individual anchor permanent displacement during nth loading	L

Development of Simulation Requirements

Once the significant parameters of the problem have been established, as has been done in the preceding section, the next step is to utilize the requirement for dimensional homogenity of functional relationships to establish the requirements for simulation or modeling. The approach taken here will be that usually called the Buckingham π Theorem approach. In this problem there are a total of 20 interrelated parameters requiring three fundamental dimensions (force, length, and time) for description. The Buckingham π Theorem states that a unique functional relationship among these parameters may be expressed as a relation among 20-3 = 17 dimensionless groups which are independent combinations of the 20 original parameters and are complete in the mathematical sense. The next step is to extablish an independent, complete set of 17 dimensionless groups. Although various formal techniques are available to accomplish this goal, it may be readily achieved by inspection.

The following 17 independent dimensionless groups have been selected:

π_1	=	$M/\rho L^3$
π_2	=	FT^2/ML
π_3	=	f
π_4	=	MV^2/BL^3 (π_2, π_3, and π_{10} omitted when π_4 included)
π_5	=	l_i
π_6	=	θ_i
π_7	=	n
π_8	=	K/BL
π_9	=	ϕ
π_{10}	=	BL^2/F
π_{11}	=	b_i
π_{12}	=	G/B
π_{13}	=	g_i
π_{14}	=	C/BT (or CV/BL when using V and not F, T, $f(t/T)$)
π_{15}	=	μ/C
π_{16}	=	Z/L
π_{17}	=	z/L

These dimensionless groups are subject to the following physical interpretation:

π_1 represents the ratio of mass or inertia effects of the weapon to these effects in the soil.

π_2 represents the ratio of impulses due to the applied force to the change of momentum of the weapon mass.

π_3	involving the dimensionless force function, leads to the requirement that this function be identical in model and prototype.
π_4	involves the ratio of kinetic energy of the mass of the weapon to the energy absorbed by deformation of the soil.
π_5, π_6	are associated with the requirement that geometric similarity be maintained between foundation elements in model and prototype and between soil specimens.
π_7	indicates that equivalent deformations will occur after the same number of applied impulses.
π_8	represents the ratio of spring force to resisting soil forces.
π_9	is associated with the simulation requirement that the angle of friction of full-scale and model soils be identical.
π_{10}	involves the ratio of the weapon forces to the resistance forces in the soil.
π_{11}, π_{13}	involve the requirement for equivalent functional relationships between stress and strain in the model and full-scale in compaction and in shear.
π_{12}	is the ratio of shear strength to compaction strength of the soil.
π_{14}, π_{15}	these ratios involve the relationship of soil viscous to nonviscous deformation.
π_{16}, π_{17}	these two response parameters involve the ratio of displacement to characteristic length.

Exact simulation of the problem under consideration requires that the dimensionless groups π_{1-15} be identical in model and in full-scale in order that the response parameters π_{16} and π_{17} be identical in model and full-scale, thus allowing accurate quantitative prediction of full-scale behavior from model test results.

Analysis of Requirements

The simulation or modeling criteria included in the requirements for equality of each of the above π terms between model and full-scale require only that the various ratios and functions involved be identical in model and in full-scale tests. Nevertheless, at present it appears necessary to utilize the same soil in model and prototype rather than to attempt to create a model soil with appropriate properties. This necessity arises due to the current impossibility of adequately defining the properties and relationships involved; thus, the necessity for relying on the use of the same soil to make sure that all functional relationships, etc., are properly duplicated—thus accounting for the lack of knowledge presently existing.

Adopting the convention that

$$(\ )_r = \frac{(\ )\ \text{model}}{(\ )\ \text{full-scale}}$$

the similitude requirements are that, in order that $\pi_r = 1$ for π_{16} and π_{17}, the ratios $\pi_r = 1$ for π_{1-15} be maintained. Adopting the seemingly unavoidable approach that the same soil be used in model and in full-scale means that all soil parameter ratios are automatically equal to 1 between model and full-scale, i.e., $\rho_r = 1$, $\phi_r = 1$, $B_r = 1$, $b_{ir} = 1$, $G_r = 1$, $g_{ir} = 1$, $C_r = 1$, and $\mu_r = 1$. Further, the requirements for equality of ratios π_3, π_5, π_6, and π_7 indicate that the functional relationship of model and full-scale forcing functions be identical, that model and full-scale anchors and soil specimens be geometrically similar and that the deformations considered must be associated with the same impulse number in model as in full-scale. In view of the results just obtained, the modeling or similitude requirements remaining are reduced to the following set.

$$\pi_1: \quad \frac{M}{L^3} = 1$$

$$\pi_2: \quad \frac{FT^2}{ML} = 1$$

$$\pi_4: \quad \frac{MV^2}{L^3} = 1$$

$$\pi_8: \quad \frac{K}{L} = 1$$

$$\pi_{10}: \quad \frac{L^2}{F} = 1$$

$$\pi_{14}: \quad \frac{1}{T} = 1$$

or

$$\frac{V}{L} = 1$$

Examination of the requirements associated with the preceding remaining equations indicates that these equations may be satisfied only for a length ratio equal to 1, i.e., for no geometric scaling whatsoever. This means that for the set of parameters chosen, exact simulation is not possible using the same soil.

The omission, from the list of parameters given, of time-dependent or viscous effects makes it possible for modeling to be accomplished using the same soil, however. This results from the fact that, when viscous effects are neglected, the terms π_{14} and π_{15} are no longer present. The remaining simulation requirements, involving π_1, π_2, π_4, π_8, and π_{10}, may then be met with length ratios other than unity. The question then arising is: Are displacements of a viscous nature negligible compared with other displacements considered? In view of the short times involved during impulsive loading and in view of the requirement that the weapon not sink significantly due to gravitational forces, it seems probable that the neglect of viscous deformations will be justified; this can only be verified by experiments, however. Neglecting the time-dependent or viscous portion of the deformation involves the neglect of parameters 17 and 18, C and μ, and the subsequent removal of the requirements associated with π_{14} and π_{15}. In this case, the final simulation requirements reduce to those given above, with π_{14} omitted.

The exact nature of these remaining requirements may be seen from a simple example. If a length ratio of 1/5 is chosen, i.e., L_r = 1/5, the requirements given lead to the following results.

π_1:	M_r	=	1/125
π_2:	T_r	=	1/5
π_4:	V_r	=	1
π_8:	K_r	=	1/5
π_{10}:	F_r	=	1/25
π_{16}:	Z_r	=	1/5
π_{17}:	z_r	=	1/5.

In order that simulation be achieved, the model system must therefore be geometrically scaled to 1/5 size, its mass must be smaller by a factor of 125 as compared with the full-scale, either the initial velocity ratio must equal 1 or the force ratio reduced by a factor of 25 and the time ratio by a factor of 5, and the spring constant must be reduced by a factor of 5 for the model system.

Several other comments are required at this time. First, if the soil specimens are extremely large compared with both model and full-scale foundation geometries, and if they are perfectly homogeneous, then no soil length parameters are necessary. If, however, the soil specimens are in boxes or bins which are not sufficiently large, it is necessary to test the models in bins which are modeled geometrically by the same factor as is the weapon anchor configuration. This is required since the flexibility or relative rigidity of the container significantly influences the response of the contained soil. In addition, when stress wave effects are significant, then this must be done to properly account for wave reflections, etc. Also, if layers are present in the soil, they must be modeled in thickness using the same length ratio as the foundation model. Each layer would, of course, have to be identical in composition and properties with the corresponding layer in the full-scale situation.

The similitude analysis presented above indicates the probability that modeling will be feasible so long as rate effects and viscous effects are negligible. The next step required is an experimental investigation to verify the above analysis for completeness, to justify the neglect of rate effects, and to determine the limitations on the assumption of negligible viscous deformation.

3. FIRST EXPERIMENTAL SERIES

The similitude analysis presented in the preceding section indicates the probability that scale model tests can be used to predict accurately the quantitative response of weapon foundations in soils if certain seemingly reasonable assumptions are valid. The next step in this effort was to carry out a series of preliminary tests to verify the basic approach and to provide insight into the general dynamic response of soils to impulsive loads. Several advantages of this approach were contemplated. First, it was hoped that this preliminary series would either prove the approach infeasible, in which case a minimum expenditure of effort would have taken place, or would prove the approach probably feasible, at least to a degree sufficient to justify further effort. Further, this preliminary series of tests was expected to considerably reduce the number of parameters considered significant to the problem and thus simplify appreciably the problem of development of soil property measuring devices.

The first decision made in the planning of these tests was to confine testing to soil samples prepared in boxes or bins rather than to make field tests. There were several reasons for this decision. First, in situ soils occur usually with significant layering, a wide variation in particle size, with a high degree of inhomogeneity and anisotropy. In addition, it would be very difficult to find field locations with an appropriate selection of soil types and conditions. Due to the lack of uniformity and control of specimens, it was decided to concentrate on tests in bins or boxes.

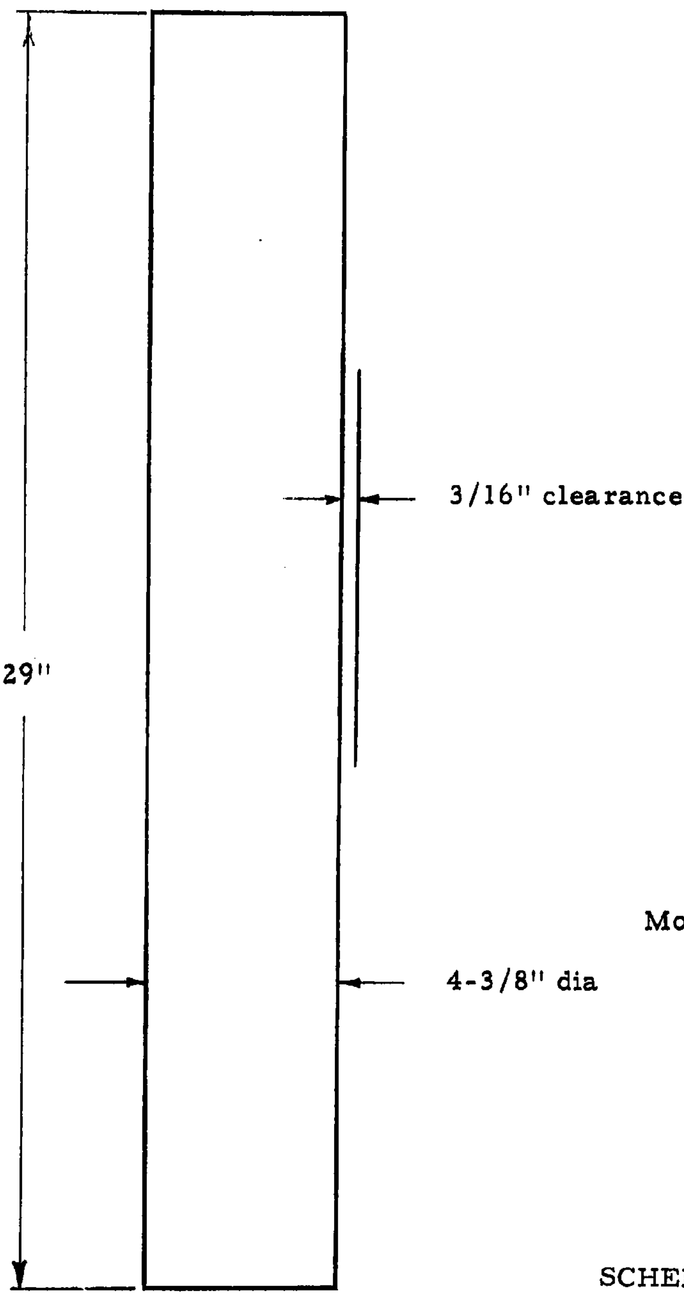
General consideration of the mechanical properties of soils throughout their range of behavior led to the decision to examine experimentally the feasibility of modeling for three typical types or classes of soils. The types selected were:

1. A coarse-grained soil, called a sand
2. A soil of intermediate grain size, called a silt
3. A fine-grained soil, called a clay.

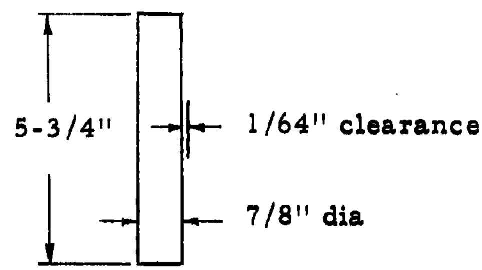
The goal of these tests was to verify the feasibility of modeling of the response of impulsively-loaded elements in soils and to establish the level of accuracy which might reasonably be expected if the same soil is used in model and prototype tests. This series of tests was not particularly concerned with the exact size of deformations of foundation elements, but rather in the accuracy with which a full-scale response could be predicted from model response. Since the problem of modeling of response to inclined loads is no different basically from the problem with vertical loads, the latter was selected for simplicity. Further, an approach was sought which involved only a mass with an appropriate initial velocity so that mechanical problems of modeling load force-time histories could be avoided. To accomplish these objectives, two drop devices were designed and fabricated. These drop devices, hereafter called model and full-scale drop devices, were designed according to the similitude requirements given in the preceding section and involved a cylindrical steel model hammer weighing 1 pound (with dimensions shown in Figure 1) and a cylindrical steel full-scale hammer weighing 125 pounds (dimensions shown in Figure 1). The large device utilized a square box, filled with soil, with dimensions as shown in Figure 2. Tests with the small device were made in small boxes, with dimensions 1/5 those of the larger boxes. Figure 3 shows a photograph of the small drop device mounted on a small box and a photograph of the large drop device mounted on a large box. It is noted that all dimensions are in the ratio of 1 to 5.

In each test, the soil within the box was completely removed and then replaced with an appropriate preparation technique. The drop devices were then clamped to the boxes and adjusted to assure a vertical drop. Cumulative penetration of each hammer was measured after each drop, the full-scale hammer to the nearest one-hundredth of an inch and the model to one-thousandth of an inch. The success or failure of the modeling effort was then determined by the accuracy with which the model displacement approached 1/5 of the full-scale displacement. Velocity control was maintained through accurate measurement of drop height.

Qualitatively, the results for all tests were quite similar; the displacement of both full-scale and model hammers was the maximum on



Large Hammer Dimensions



Model Hammer Dimensions

FIGURE 1

SCHEMATIC OF DROP HAMMERS

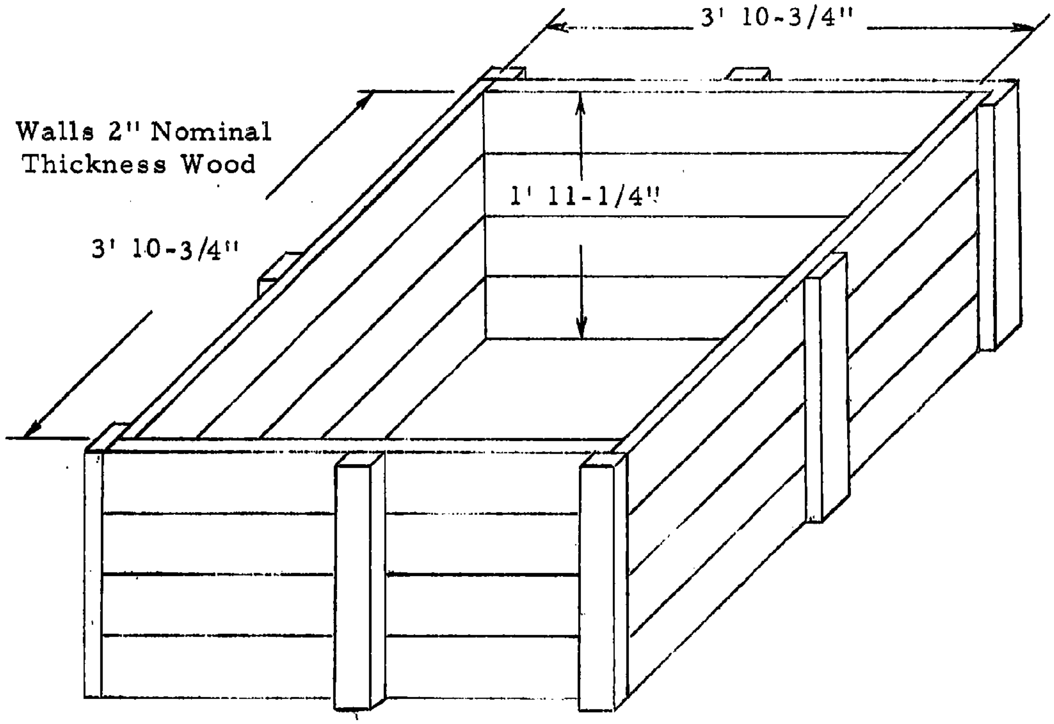


FIGURE 2

LARGE SOIL BOX

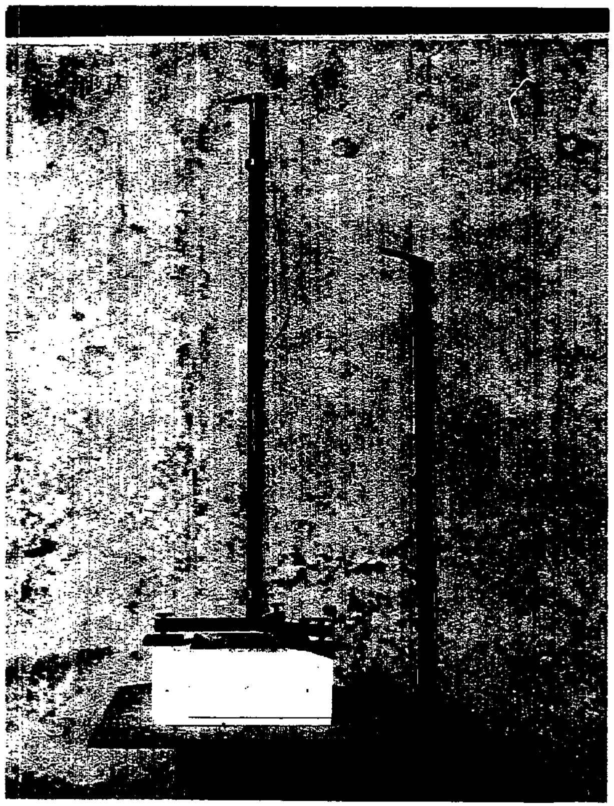


FIGURE 3

DROP TEST DEVICES

the first drop and gradually diminished in subsequent drops in regular fashion as indicated by the typical curves shown in Figure 4. Comparison of results could be made on a drop-by-drop basis or shown as ratios of cumulative displacement after each drop; however, consideration of cumulative penetration is felt to be more meaningful since discrepancies between individual drops are averaged out.

Before describing experimental results, it is appropriate to comment on several sources of inaccuracy and inconsistency which were present in these tests. Probably the most serious source of difficulty involved failure to exactly duplicate soil characteristics in the model and in the full-scale situations. This difficulty involved both variations in moisture content and variations in preparation and compaction techniques. Another significant difficulty involved the slight clearance necessary in the drop device and the accompanying variation from identical impact locations. When this occurred, a small quantity of soil would be sheared from the side of the hole and thus alter the results obtained. Another source of error involved unequal drying effects of the surfaces of the soil samples and small surface irregularities. These effects would be more significant for the model than for the full-scale device and would thus introduce small errors in modeling.

The tests described below were intended to provide information on rate effects, the relative importance of kinetic energy and momentum characteristics, and size or length effects for soils of varying

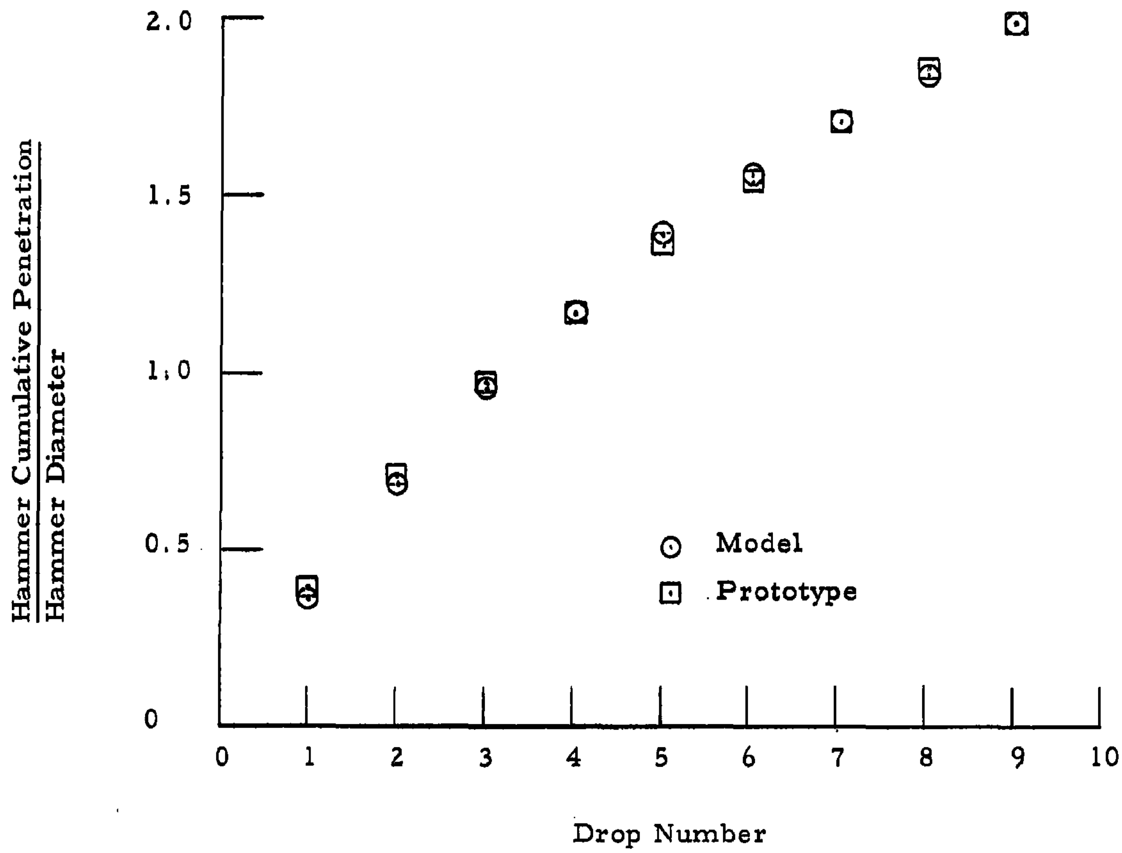


FIGURE 4

PENETRATION IN LAYERED SAND SPECIMENS

degrees of moisture content. In each of the series described below, tests were made for soils with very small moisture content, i. e., dry soils, soils with intermediate moisture contents, and soils with very high moisture contents, i. e., saturated. Although actual deformations involved varied considerably, the moisture content did not seem to influence appreciably the modeling accuracy; therefore, no distinction as to moisture content is made in the results presented below.

In order to obtain some idea of the importance of rate effects, tests were conducted with all conditions as nearly identical as possible, with the exception of initial hammer velocity. These tests included velocities of 5.6, 8.0, and 11.3 ft/sec. For all velocities, the results were equal within the range of experimental error; it was concluded that deformation rate effects, at least in this velocity range, are not significant.

Tests to determine the relative importance of kinetic energy and momentum effects involved use of the small device and box only. Specimens were identical and tests varied only in hammer size and velocity. Three different experimental arrangements were investigated. These were:

Set 1

Hammer weight:	1 pound
Hammer velocity:	8.0 ft/sec

Set 2

Hammer weight:	5 pounds
Hammer velocity:	1.6 ft/sec

Set 3

Hammer weight:	5 pounds
Hammer velocity	3.6 ft/sec

The 5-pound hammer was identical in diameter with the 1-pound hammer shown in Figure 1, and had a length 5 times greater. The velocity and mass of Set 2 were such that the momentum is identical with Set 1, whereas kinetic energy is not. In Set 3, the velocity and mass are such that kinetic energy is identical with Set 1, whereas momentum is not. The results of these experiments indicated that soil response was much more sensitive to kinetic energy variations than to momentum variations. Specifically, results of experiments of Set 3 agreed within approximately 10% of those of Set 1, whereas the results of the experiments of Set 2 varied by 50% and greater. The comparison of results of Set 3 and Set 1 were not considered sufficiently good, however, to allow modeling based only on kinetic energy considerations alone and therefore work continued to model both momentum and kinetic energy.

A major portion of this first experimental series involved investigation of the influence of various sizes or length parameters, primarily those associated with depth of soil and layering. The similitude analysis presented in the preceding section of this report indicated that it would probably be necessary to model depth and thickness of layers. These tests were intended to determine the necessity and feasibility of such modeling considerations.

First, experiments were made for various conditions of layering and compaction with both model and full-scale hammers dropping onto the surface of the large box filled with soil. In none of these cases was it possible to consistently obtain the predicted 1/5 ratio of model displacements to full-scale displacements. Next, tests were made for the large hammer on the large box filled with a single relatively uncompacted layer of soil, and the results compared with those of small hammer tested in the small box containing a single layer of relatively uncompacted soil. These results were sufficiently close to the 1/5 ratio that it was considered feasible to try to model multiple layer effects.

The final series of tests involved the preparation of samples of soil in five equal compacted layers, each of approximately 4 inches in thickness in the large box and 4/5 inches in thickness in the small box. Test results with these two configurations were unsatisfactory until the tamping or compaction procedure was carefully modeled. This was accomplished as follows. The soil in the large box was compacted using a tamper weighing 25 pounds, with a contact surface 6" x 6", and dropped from a height of approximately 4 inches with each layer uniformly tamped twice. The tamper for the small box was dynamically modeled on the basis of kinetic energy equal to 1/125 that of the large tamper. The resulting tamper weighed 0.80 pounds, had a contact surface 1.2" x 1.2" and was dropped from a height of 1". The tamping procedure was identical with that used for the large configuration.

By careful attention to modeling of layers, surface effects, etc., it was found possible to consistently predict full-scale penetration within 5% utilizing model test results for hammer initial velocities from 5 to 15 ft/sec and for various moisture contents of all three soil classes. Typical results for a moist layered sand specimen are shown in Figure 4. The cumulative permanent displacement of the full-scale device (8.700") is seen to vary from that predicted by the model test results (1.730" x 5 = 8.650") by less than one percent after nine loadings! It is certainly not expected that all model test results will be of this extremely high accuracy, obtained under careful laboratory conditions; such accuracy is, however, believed possible if sufficient care is exercised in the experimental procedure.

4. ANALYSIS OF RESULTS OF FIRST EXPERIMENTAL SERIES

Since the preliminary results of the first experimental series were similar qualitatively for all three soil classes, the conclusions drawn here will not distinguish among the different soils. Probably the most significant conclusion which can be drawn from these results is that accurate quantitative predictions (consistently within approximately 5 %) of full-scale results from model results are possible utilizing exactly the same soil in identical condition and with identical properties in model and in full scale tests. Thus, the known distortion between model and prototype of strain and deformation rate effects and viscous effects is apparently negligible since accurate results based on their omission were possible. Since the neglect of these factors was considered the most serious threat to successful modeling, it can be concluded that no fundamental difficulties exist in accurate modeling. Nevertheless, a number of aspects of the problem were brought to light which must be carefully considered and treated if a reliable modeling technique is to result. Perhaps most striking of these factors is the significance of the modeling of layers in the soil. Further, a most important consideration is the proper treatment of surface irregularities which are significantly more important for the model than for the prototype. In addition, these results indicate that no general simplifications of load/time history, such as including only kinetic energy or only momentum considerations, are feasible.

Since this preliminary series of experiments has indicated that viscous and rate effects are negligible, the soil properties selected for measurement can be restricted to those of a quasi-static nature.

In summary, the results of this first experimental series lead to the conclusion that accurate model predictions are feasible if exactly the same soil conditions are present in model and full-scale systems. The next step is to attempt to extend this modeling technique.

5. SECOND EXPERIMENTAL SERIES

Soil Properties

In order that the modeling techniques presented be extended, allowing test results from one soil to be used to predict results in another soil, it is necessary to have an adequate mechanical description of the soil properties. The next step in this research effort was therefore to select a preliminary set of properties, develop means of measuring these properties, and then investigate the correlation between this set of properties and foundation behavior.

As discussed in the preceding section, the soil properties may be divided into a number of categories. Here, it is convenient to group these properties as:

1. Inertial characteristics
2. Frictional characteristics
3. Elastic/plastic shear characteristics
4. Elastic/plastic compression characteristics

These categories of soil behavioral characteristics will be discussed individually, together with the choice of experimental procedure defining each characteristic.

1. Inertial Characteristics. As discussed in the preceding section, a single initial soil mass density ρ is considered as the only parameter necessary to describe soil inertial properties. Of course, the mass density will change with compaction but this change is believed adequately included through incorporation of the soil compression

characteristics. This parameter will be obtained by the measuring techniques described in Appendix A.

2. Frictional Characteristics. Soils in general exhibit frictional behavior in the nature of a coefficient of friction or angle of internal friction relating shear stress and the normal stress on a shear plane during shear flow. Although various nonlinearities have been observed for various soils, the general frictional behavior is believed adequately described by the specification of a single parameter ϕ defined in the preceding section. The measurement technique for determining this parameter is described in Appendix A.

3. Elastic/plastic Shear Characteristics. An evaluation of various studies on the dynamic behavior of soils* led to the conclusion that the significant shear characteristics could be adequately described by using the maximum shear strength of the soil, i.e., strength at failure, in the absence of normal forces on the plane of failure. In addition, in order to include some measure of the effect of compaction on shear strength, direct shear tests on soil specimens which had been previously subjected to normal compressive stresses were included.

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* The report "Mechanical Properties of Earth Materials," DASA 1285, Part II by R. V. Whitman was a particularly valuable source of information.

Both tri-axial testing and direct shear testing were considered for the determination of this maximum shear strength. Since it was believed that either of these tests would provide an adequate measure of this property, a box-type direct shear test was chosen for its simplicity, speed of operation, and the fact that the same apparatus could be used readily to determine friction angle as well as shear strength. This apparatus is described in Appendix A.

4. Compression Characteristics. The compression characteristics of soils are believed adequately described by the results of a one-dimensional, undrained compressive test made in the apparatus described in Appendix A. Due to the impulsive nature of the loads contemplated and to the resulting short times, the undrained test seemed most appropriate. Also, there is the question here of the required completeness of description of the compressive stress/strain curve resulting from this test. Such curves are known to be very nonlinear in many cases and thus not describable by a single parameter. Four different parameters have been utilized in seeking an adequate description of the curve. The technique utilized for obtaining these parameters is also described in Appendix A.

Experiments

Upon completion of the first series of experiments, described in Section 3, and the development of the soil property measuring devices described in this section and Appendix A, a comprehensive testing program was begun with two objectives in mind. First, it was desired to establish, throughout the broad range of wet and dry sands, silts, and clays, the accuracy which could be expected if the model and prototype devices were tested on the same sample of soil. This question would be particularly important when testing of models in the field on the same location for which full scale predictions would be desirable. The second objective of this program was to determine how accurately basic soil properties would predict the dynamic cumulative penetration of the drop devices. This information was desirable in order to determine the meaningfulness and completeness of the selected set of soil properties and thus establish the completeness of the mechanical description of the dynamic soil response by these properties. The completeness of this set of properties is, of course, directly related to the feasibility of extrapolating and interpolating the predictions of model test results to different soil conditions.

This series of experiments was carried out in a manner quite similar to those described in Section 3. Certain significant changes were made, however. One important change was the provision of an anvil which would remain in contact with the soil at all times. Figure 5 shows the hammers and anvils which were used in model and in full-scale tests. Note that the hammers fit inside the anvils, impacting the anvil bottoms and thus the anvil movement is essentially stable. The inclusion of these anvils was necessary in order to eliminate problems of material

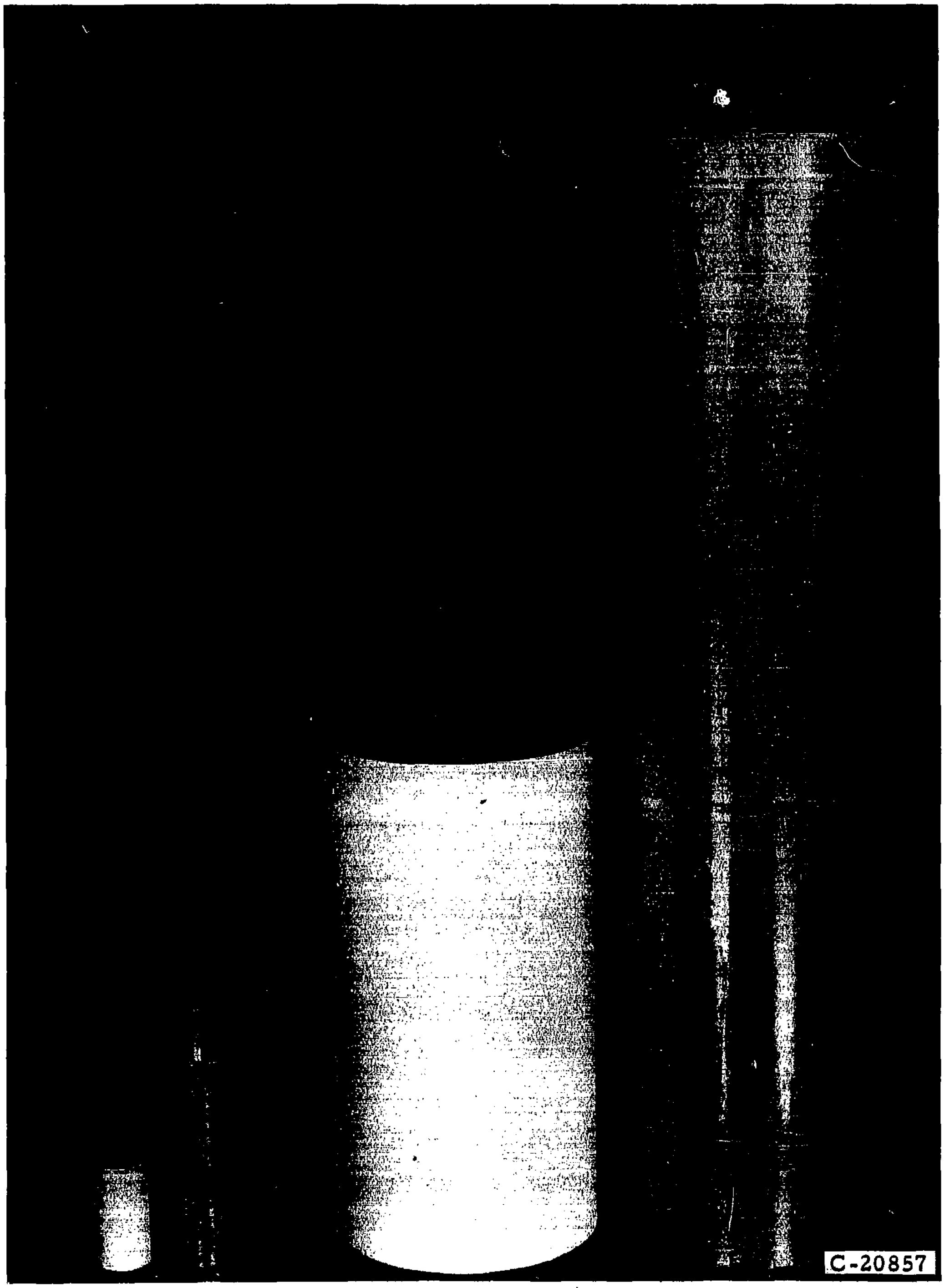

FIGURE 5

MODEL AND PROTOTYPE HAMMERS AND ANVILS

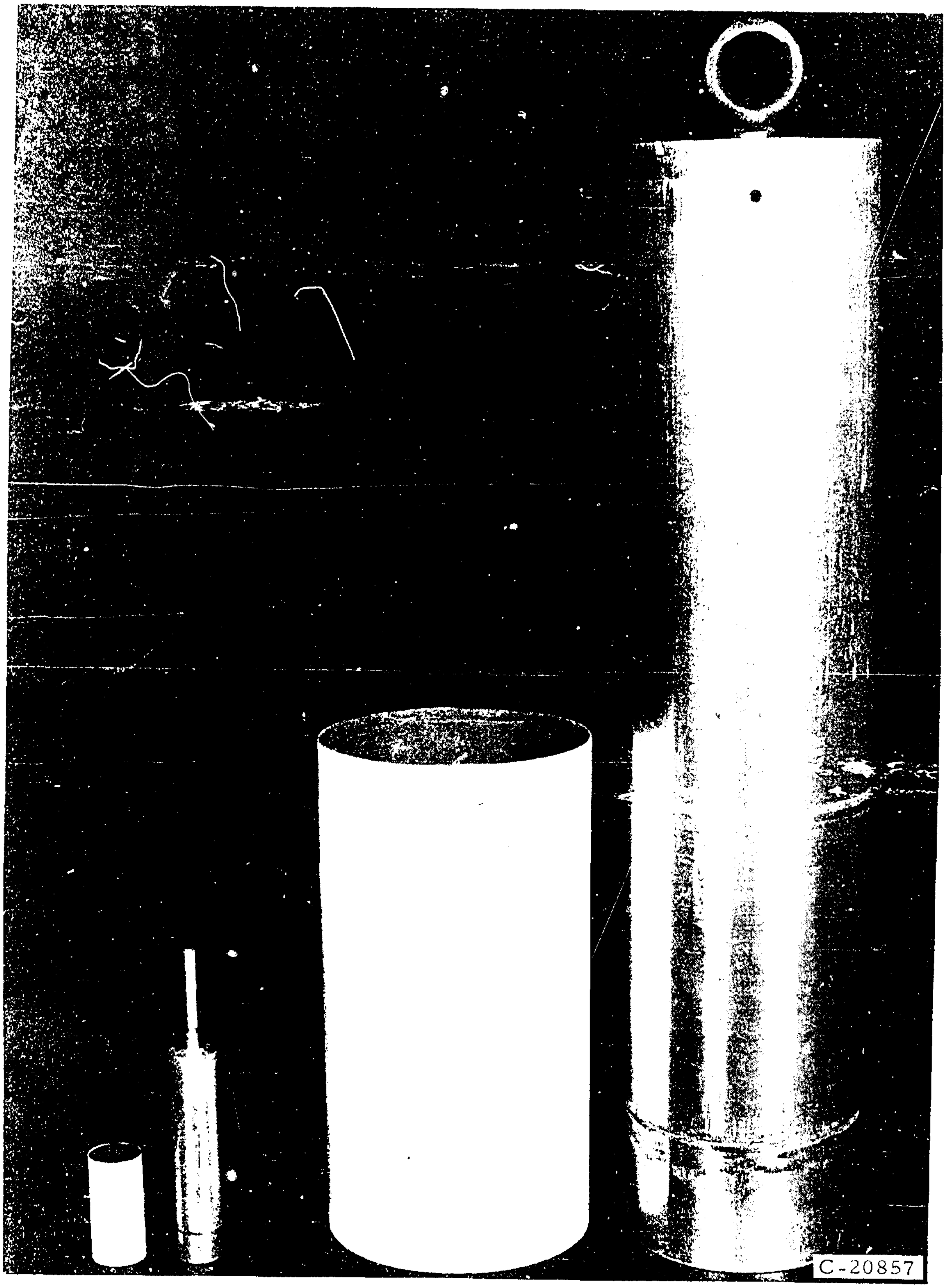

FIGURE 5

MODEL AND PROTOTYPE HAMMERS AND ANVILS

falling into the holes between impacts. These anvils were made of steel and the model anvil was a precise 1/5 linear-scale replica of the full-scale anvil thus satisfying the model criteria discussed previously. The model and full-scale anvils were 1.00 inches and 5.00 inches in diameter and weighed 0.68 lbs. and 8.50 lbs. respectively. The hammers in these tests were made of aluminum with model and full-scale weighing 1.00 lbs. and 12.50 lbs. respectively. As in the previous series of tests, the small soil bin or box was a precise 1/5 linear model of the large one. Since rate effects had been proven negligible, this entire series of tests utilized hammer initial velocities of 14.6 feet/second, chosen as an appropriate compromise figure, considering the impulses and masses associated with actual weapons.

The first set of tests of this series involved 10 pairs of dynamic tests, a pair of tests being one large box, large device test and one small box, small device test. The range of soil conditions utilized was as follows. Four tests of sand class soils were made, one being a test of sifted loose dry sand, a second of moist, damp sand which was compacted in layers as described in Section 3, a third being a completely saturated sand in which water was standing slightly on the surface, and a fourth a test on sand which had been completely saturated and then allowed to drain. Silt class soils were tested in three conditions, a loose, dry sifted state, a layered, compacted state, and a very wet or mud state. The clay soil tests were made for the same three states as were the silt tests.

For each of the dynamic experiments run, the soil properties (described in Appendix A) of compression, shear, friction and density were measured. The results of these tests were then analyzed statistically as described in the following section and Appendix B to determine how well the results could be predicted from the basic soil property measurements. The results of this first test set indicated that the basic set of soil properties was adequate for the identification of the soil from the dynamic point of view but that no worthwhile prediction equation was feasible which would allow prediction based simply on the results of these independent basic property tests. It was thus deemed desirable to make a second series of tests and to include a less basic measurement of the soil properties which would combine soil behavioral characteristics in such a way as to better correlate with the dynamic penetration results. A second set of tests was run, similar to the first described but with the added measurement of a 60° cone penetrometer as described in Appendix A. The results of this test set indicated that the correlation between dynamic penetration results and penetrometer results was far better than for any of the basic soil properties individually. It was thus decided to make a third and final set of tests in which penetrometer readings using various different cone figurations would be made. In this last set of tests, three cone configurations, with 30°, 60° and 180° included angles as shown in Appendix A, were used and those tests involving layered soil compaction were omitted.

Since the results of this final test series will be discussed in some detail and since these results are considered typical, the entire set of data is presented in Appendix C. Note that in this set of impulsive loading tests were carried out with both large and small devices impacting the large soil specimen and with the small device impacting the small soil specimen.

6. ANALYSIS OF RESULTS OF SECOND EXPERIMENTAL SERIES

In order to make comparisons among the various results representing dynamic penetration characteristics, it was deemed necessary to arrive at some satisfactory one parameter description of each set of test results. The first step toward this goal was the examination of a complete set of curves representing the entire range of soil conditions studied. A typical set of results is shown in Figure 6. From this set it is observed that the general relation between cumulative depth of penetration and number of drops has the general form $CD = A\,n^{r}$ where CD is cumulative depth of penetration, A is a constant, n is drop number and r is a constant exponent. The approach taken was first to utilize the regression technique described in Appendix B to determine the best (in a least squares sense) value of A and r for an assumed functional relation of the form given. The best values of r resulting ranged from 0.53 to 0.94, with an average of 0.75. This value of 0.75 was then chosen for comparison purposes and the regression technique again utilized to find the best value of the A's for a functional relation of the form $CD = A\,n^{0.75}$. The A's resulting from this analysis, which are presented in Table 1, thus serve as a simple characteristic parameter describing dynamic penetration characteristics in a given soil and can be used for comparison of results in different soils.

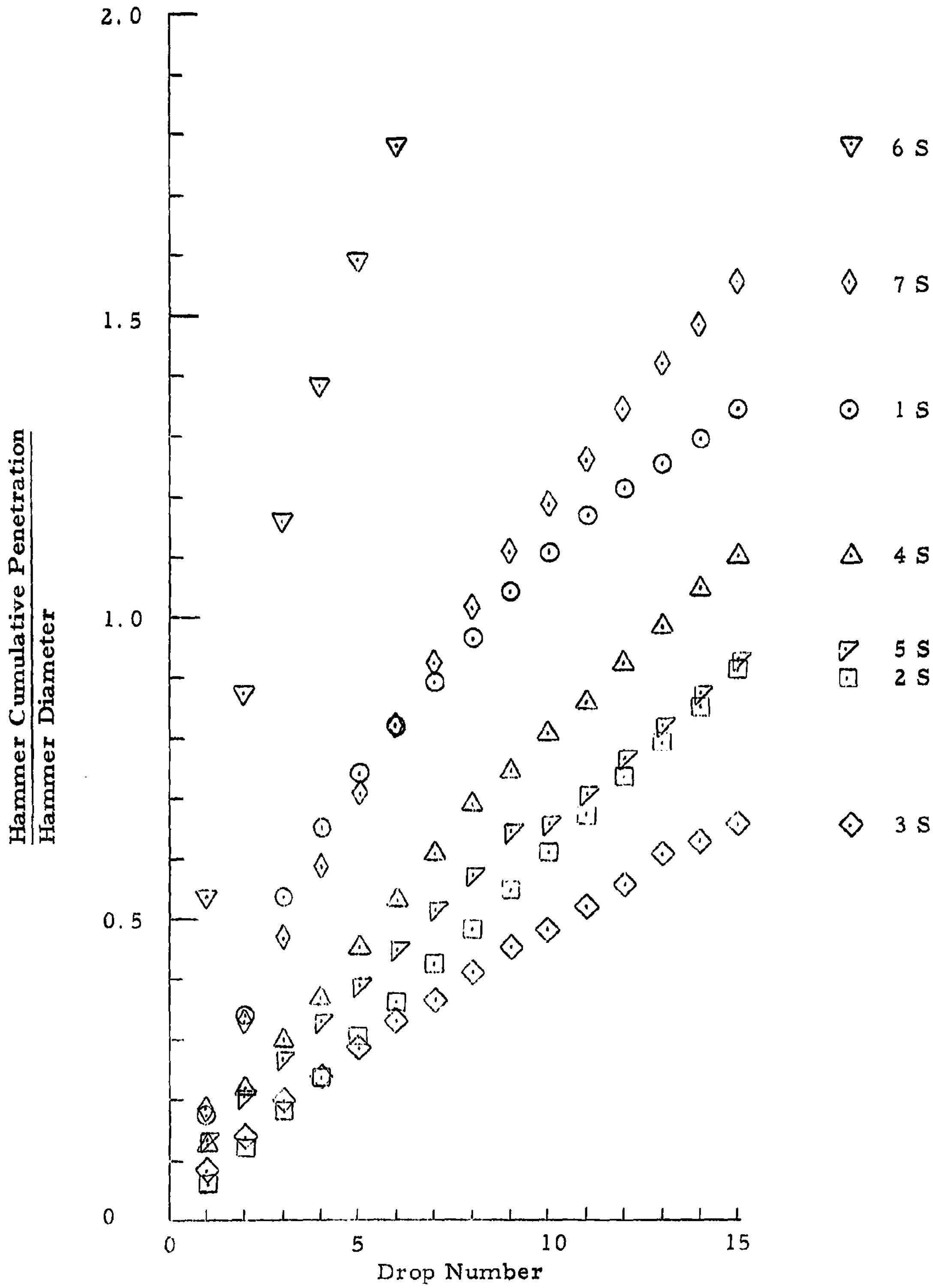

FIGURE 6

DYNAMIC PENETRATION RESULTS

TEST	A (inches)
1 L	1.81
2 L	0.606
3 L	0.315
4 L	1.68
5 L	1.13
6 L	0.673
7 L	0.475
1 LS	0.540
2 LS	0.102
3 LS	0.0414
4 LS	0.404
5 LS	0.326
6 LS	0.180
7 LS	0.119
1 S	0.192
2 S	0.110
3 S	0.0864
4 S	0.143
5 S	0.120
6 S	0.483
7 S	0.208

TABLE 1

SINGLE PARAMETER DESCRIPTION OF DYNAMIC PENETRATION RESULTS

The first comparison to be made involves the results of model and full-scale tests both performed on the large box. Specifically, the comparison will be based on how closely the model penetration values, characterized by the A values for tests LS, approach the value of 1/5 that for the tests L. From Table 1 it is seen that the ratios A_L/A_{LS} vary from 3.4 to 7.6, whereas the correct ratio would be 5.0. A similar comparison, based on actual cumulative penetration figures for the maximum n obtained taken from Appendix C, shows a range of A_L/A_{LS} of from 3.6 to 7.4. The first conclusion to be drawn from these results is that the A values provide meaningful representations of the penetration results in the various soils. The second conclusion is that errors as high as 50% can be expected when the model device is tested on the same soil specimen as the full-scale device and the effects of layering, inhomogeneity with depth, surface conditions, etc. are not properly modeled. This result is of considerable importance in field testing since it means that if a model device is tested in the same location as the full-scale device, then high accuracy cannot be expected.

The second comparison of results to be made involves the accuracy with which the dynamic penetration might be predicted from the results of the soil property tests. Thus, the strength of the correlation between soil properties and dynamic penetration results is to be determined in order that estimates be made of the accuracy with which test results in one soil can be extrapolated or interpolated to another soil with different properties. Since in earlier tests of this series, it was found that very little correlation could be found between dynamic penetration results and the basic soil properties of shear, friction, compaction and density, these were omitted and only the three penetrometer readings were considered. For this comparison, a relationship of the form $A = a_o + \frac{a_1}{P_1} + \frac{a_2}{P_2} + \frac{a_3}{P_3}$ where the a's are coefficients to be determined and P_1, P_2, and P_3 are the readings for the 60^o, 30^o and 180^o penetrometers. The values of the a's, as determined by a regression analysis, which minimized the standard error in the A's, were obtained. These values were then used with the actual penetrometer results to predict A values for each curve and these in turn used to predict cumulative penetration. The final comparison is thus between the actual observed values and those predicted from the penetrometer test results. The predicted and observed values for the largest n value obtained, are presented in Table 2 for the large device, large box set. From this table it is seen that the predicted values differ from the observed values by as much as 50%. It may be concluded, therefore, that the penetrometer readings taken provide a mechanical definition of the soil such that errors in the order of 50% may be expected if extrapolation of test results based on these is made from one soil to another.

The final determination of this series involved a comparison between predictions of prototype behavior based on model test results from different soil conditions. This comparison thus combined modeling and

TEST	MAX. n	PREDICTED MAX. CD (inches)	OBSERVED MAX. CD (inches)
1 L	10	7.77	9.53
2 L	15	4.27	4.69
3 L	15	2.87	2.48
4 L	12	11.49	9.93
5 L	15	9.24	7.87
6 L	15	7.80	4.90
7 L	15	2.71	3.38

TABLE 2

COMPARISON OF PREDICTED CUMULATIVE DYNAMIC

PENETRATION RESULTS WITH OBSERVED RESULTS

FOR TEST SET L

soil mechanical description. The approach taken was to utilize model test results of a small box, small device nature, determine the best value of the coefficient A in the relationship $CD = An^{3/4}$ by use of a regression technique as described in Appendix B, next determine the best coefficients (a's) in a relationship $A = a_0 + \frac{a1}{P1} + \frac{a2}{P2} + \frac{a3}{P3}$ and finally to use the resulting coefficients together with the penetrometer readings associated with large device/large box tests to predict the results of these large box/large device tests. It was, of course, necessary to multiply the coefficients by the scale factor 5. The final comparison made was to compare the prediction for the large box, large device result with observed results. This comparison showed that the predicted values might be as much as a factor of two different from the observed values.

In summary, the results of this final series of tests have indicated that differences in the order of 50% may be expected between 1/5 scale model predictions and observed prototype results if both model and prototype are tested on the same soil specimen, such as would occur in field tests, and that differences in the order of 100% may be expected between 1/5 scale model predictions extrapolated to different soil conditions using the three penetrometer soil mechanical descriptions described.

7. CONCLUSIONS

The research program described in this report is believed to allow the following conclusions to be drawn. First, the use of small scale dynamic models to predict accurately full-scale foundation behavior has definitely been proven feasible throughout a broad range of possible soil conditions. It has been found, however, that accurate predictions (within 5%) were possible only when tests were performed on carefully prepared soil specimens in which layers, surface effects, etc., were properly modeled and the soil at corresponding points had identical properties in model and prototype specimens. Further, it was found that accuracy levels of only 50% could be expected if model tests were made in the conventional field test manner on the same location as prototype tests and that extrapolation of model test results from one soil to another would probably involve errors in the order of 100%. These results also indicate the probability that a large number of experiments will be necessary, since extrapolation of results with high accuracy does not appear feasible, and thus that the cost savings due to the use of model tests as compared with full-scale tests will be very significant.

The final conclusion of this report is therefore that a verified modeling technique has been developed which will allow the use of models to generate the quantity of experimental data necessary for the development of a weapon foundation design handbook.

APPENDIX A

SOIL PROPERTY MEASURING EQUIPMENT AND TECHNIQUES

SOIL PROPERTY MEASURING EQUIPMENT AND TECHNIQUES

1. Description of Equipment

In order to obtain a relatively undisturbed specimen of the soil, a sampler as shown in Figure 7 was constructed. The sampler had an inside diameter of 2", took samples of varying depth through the use of internal spacers, and minimized sample disturbances through the use of a plunger arrangement by which the soil sample entered and left the sampler in the same direction.

A picture of the one-dimensional compression apparatus is shown in Figure 8 and the internal workings are shown schematically in Figure 9. In order that this device be portable, it was fabricated using a simple mechanical design, and for efficiency it was made compatible with the sampler so that the specimen need not be transferred from the sampler.

The direct shear device shown in the photograph, Figure 10 and schematically in Figure 11, was used to determine shear strength and frictional characteristics of soils. As shown in Figures 10 and 11, this device was loaded with the soil specimen from beneath using the sampler previously described and weights were applied to provide the normal load when friction tests were to be made.

The penetrometer device used is shown in Figure 12 and the different penetration heads are shown in Figure 13.

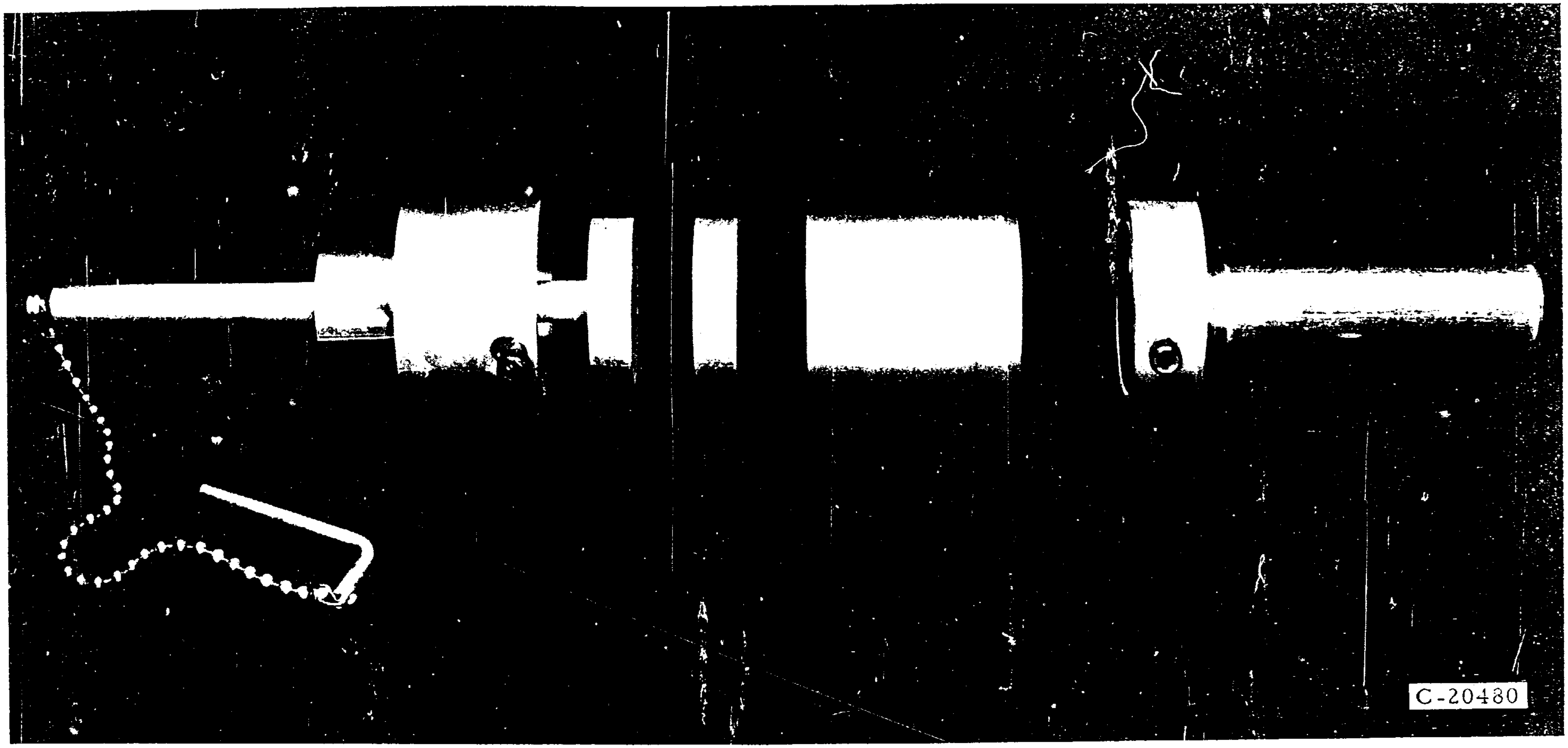

FIGURE 7

SOIL SAMPLER

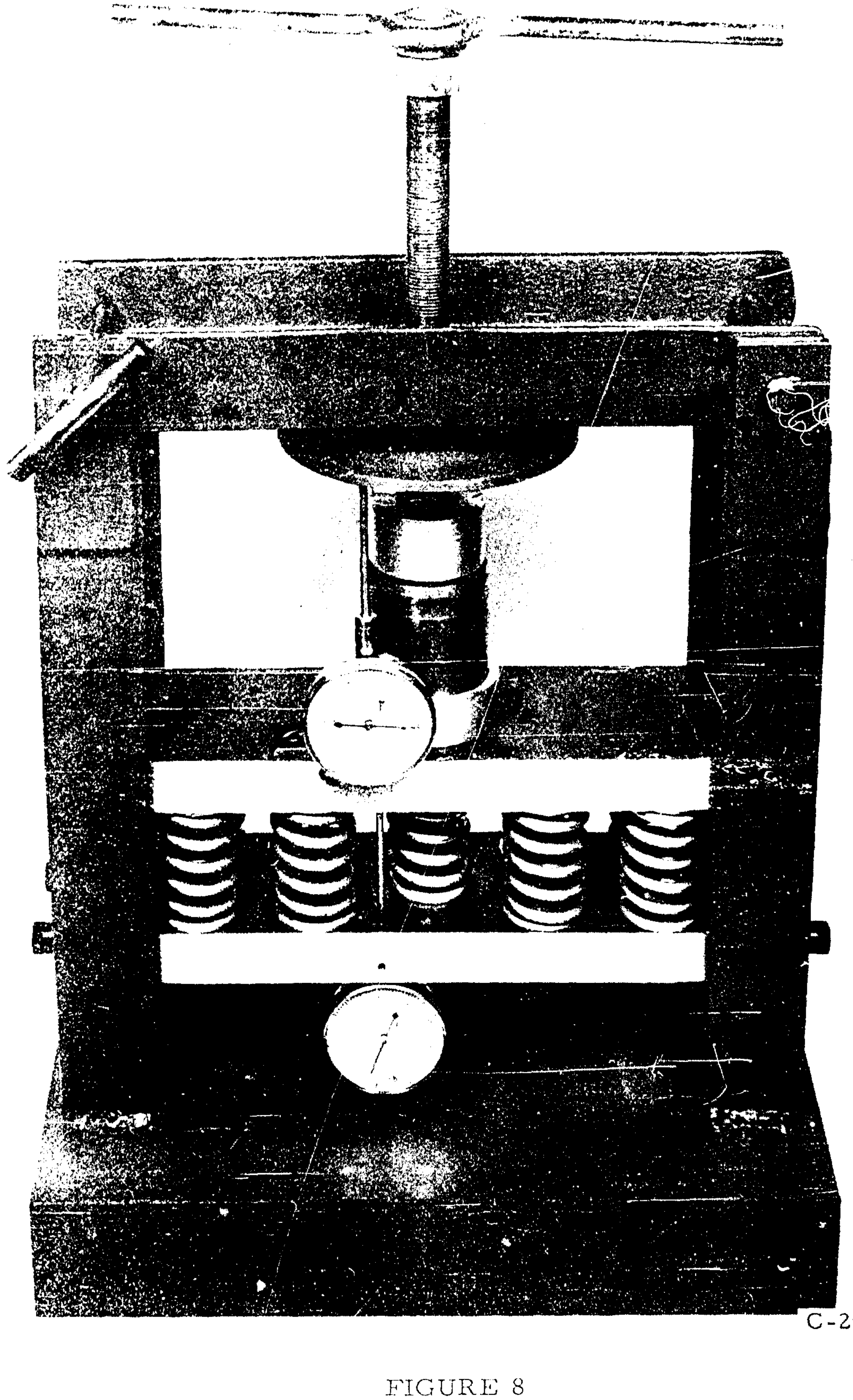

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FIGURE 8

SOIL COMPRESSION APPARATUS

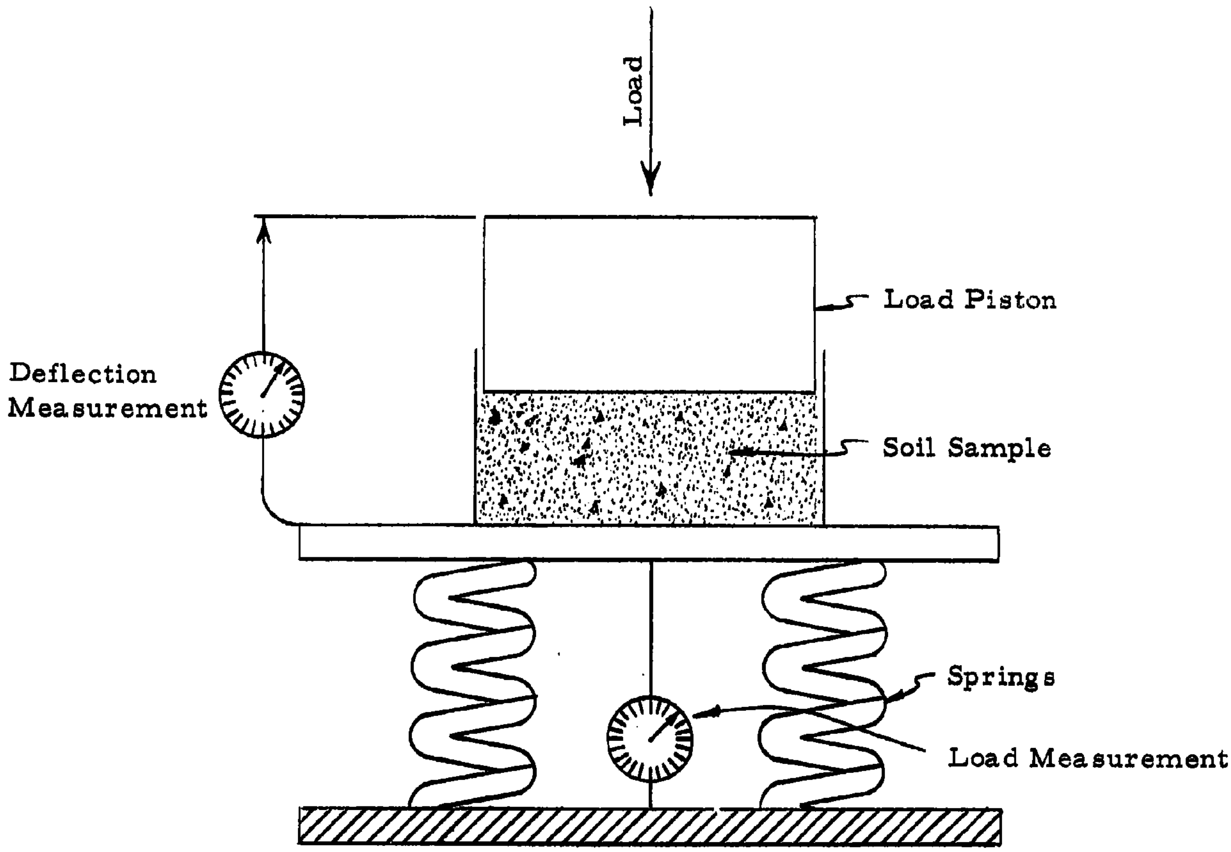


FIGURE 9

SCHEMATIC—SOIL COMPRESSION APPARATUS

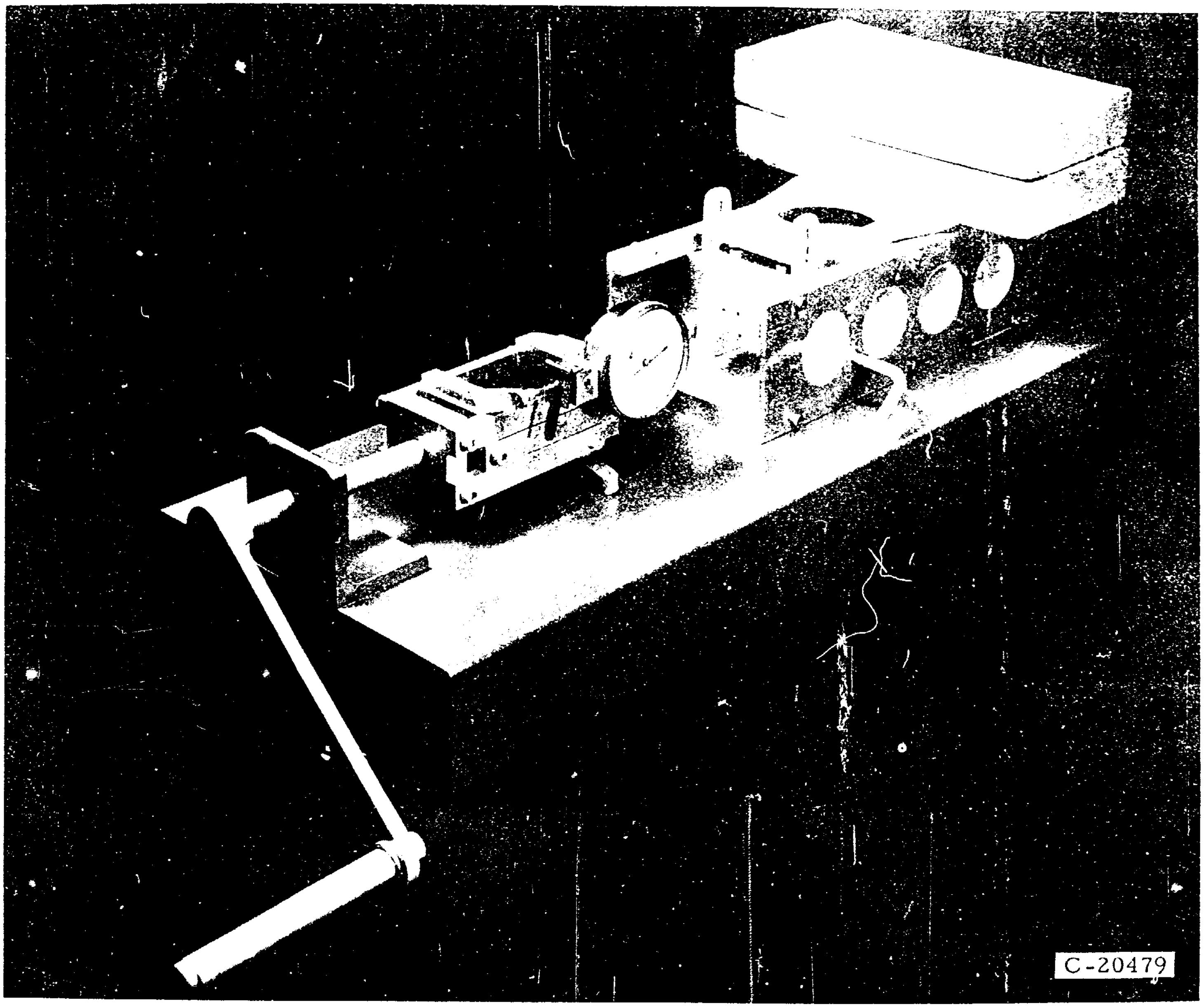
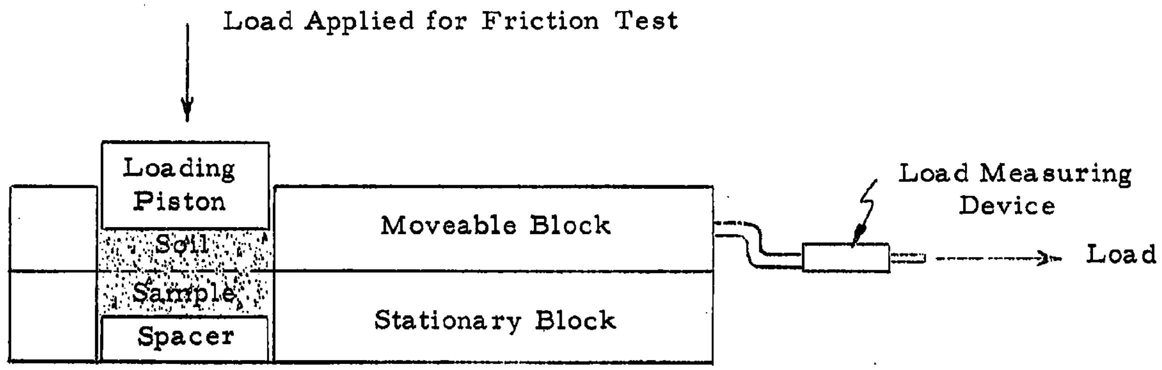
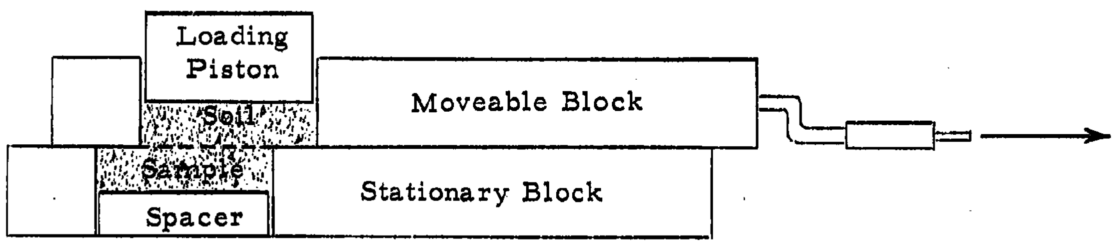


FIGURE 10

SOIL DIRECT SHEAR/FRICTION APPARATUS



Before Soil Shear Failure



After Soil Shear Failure

FIGURE 11

SCHEMATIC—SOIL DIRECT SHEAR/FRICTION APPARATUS

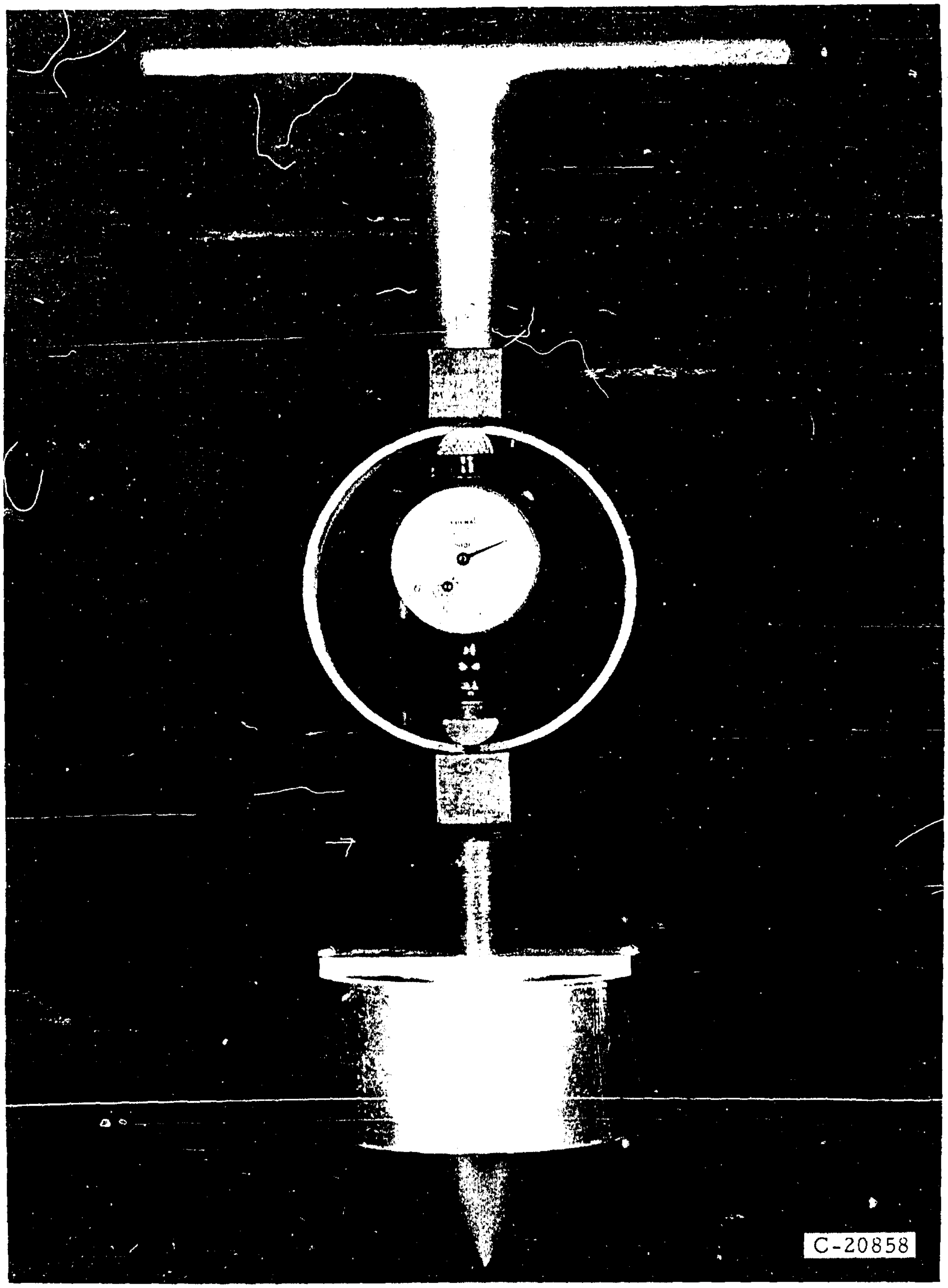


FIGURE 12

PENETROMETER WITH 60° CONE

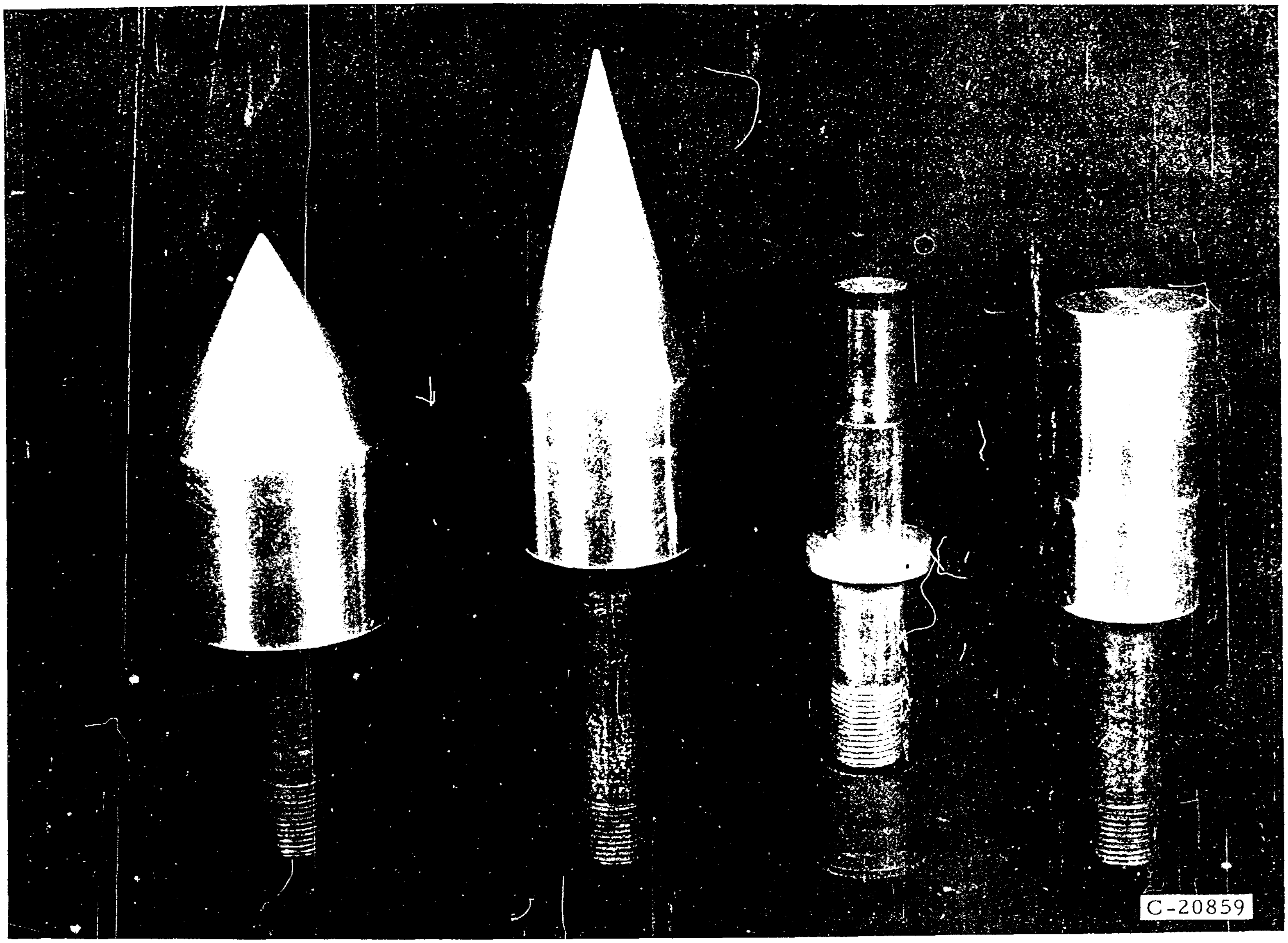


FIGURE 13

PENETROMETER HEADS

2. Measuring Techniques and Property Determinations

The density of the soil was measured by weighing the soil sample obtained using the previously described sampler and then dividing by the contained volume.

The compression properties used were determined from the compression stress/strain curves obtained as follows. First, the curve was drawn as shown in Figure 14. In order to eliminate surface effects, point A was selected as the 2 psi point on the curve. Second, an asymptotic slope line was drawn to the terminal portion of the curve. Compression property number one was then defined as the strain between point A and point B, the 2 psi point on this asymptote. The second soil property utilized was the slope of this asymptote in psi. The third compression soil property used was the slope of the straight line connecting point A and point C, which was the 20 psi point on the curve. A final soil property, the fourth, was defined as the slope of the line connecting point A and point D, the 100 psi point on the curve.

The in situ shear strength of the specimen was measured as the maximum stress during a constant strain rate shearing of the soil without normal load. The time to shear failure was in the order of 5 seconds. Also, two other shear properties were measured to try to establish a relationship between shear strength and compression. These properties were determined by first subjecting the soil specimen to uniform normal stresses of 15 and 30 psi and then removing the loads and testing to

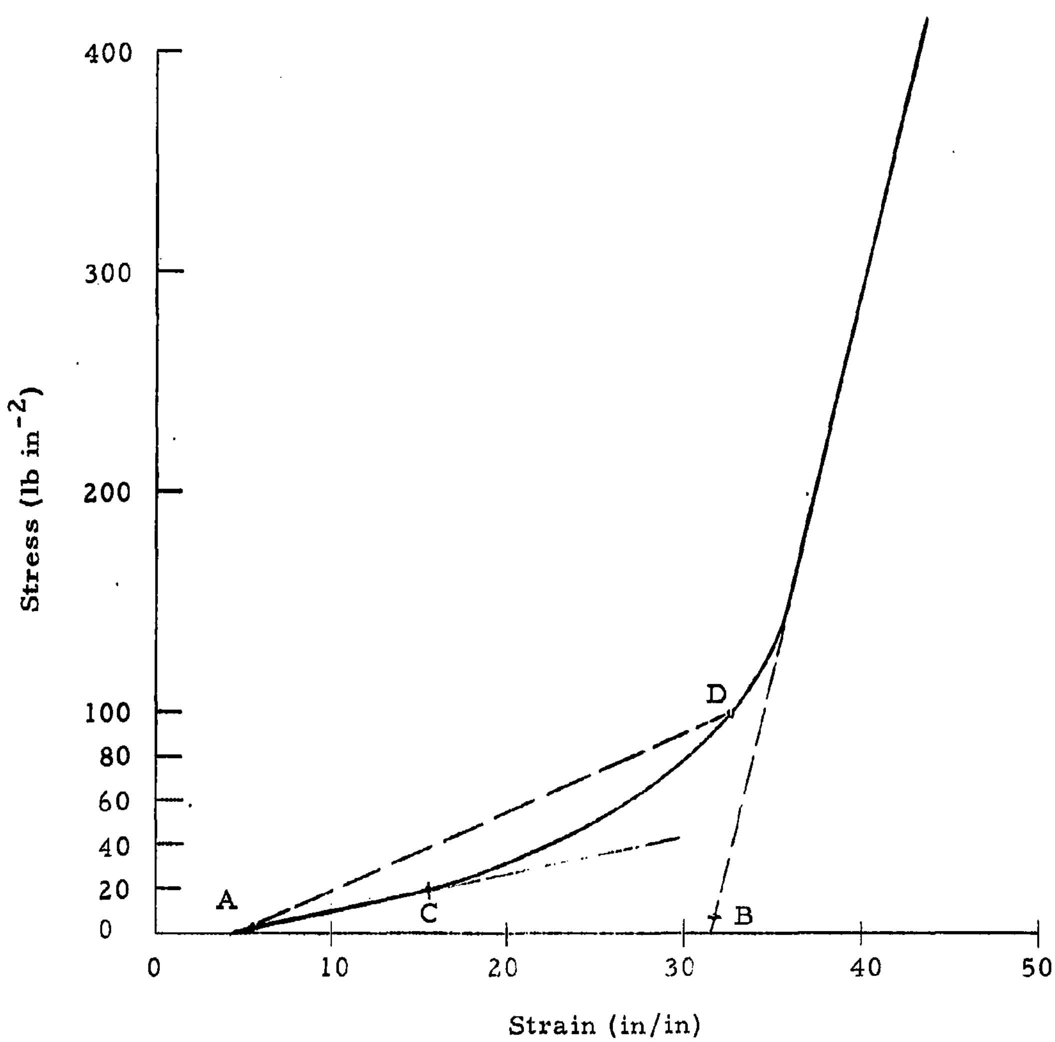


FIGURE 14

SOIL COMPRESSION STRESS-STRAIN CURVE

failure as described above.

The frictional behavior of the soils was determined by placing 48 and 96-lb normal loads on the 2" diameter specimen and then determining the force required for shear type failure.

The combined strength factors as provided by the results of the penetrometer readings were obtained as the force required for a 1-7/8" penetration of the 60° penetrometer (P_1), a 2-7/8" penetration of the 30° penetrometer (P_2), a 3/4" penetration of the 1-1/2" diameter 180° or flat-bottom penetrometer (P_3), and a 3/8" penetration of the 3/4" diameter penetrometer (P_4). In order to minimize creep effects, these tests were all carried out in approximately 5 seconds from beginning to full penetration.

APPENDIX B

REGRESSION ANALYSIS

REGRESSION ANALYSIS

Regression analysis is concerned with fitting a curve through a set of points. In general, there is a dependent variable Y which one wishes to predict from independent variables $x_1, x_2 \ldots x_m$. In linear regression, the equation takes the form

$$Y = a_o + a_1 x_1 + a_2 x_2 + \ldots a_m x_m$$

The criteria for fitting the points is to calculate values for the coefficients (a's) which minimize the sum of the squares of the error. This is known as least squares curve fitting. Letting Q denote the sum of the squares of the error, the following equation becomes the basis for the regression

$$Q = \sum_{i=1}^{n} (Y_i - \sum_{j=1}^{m} (a_o + a_j x_{ij}))^2$$

Y_i is the ith value from the experiment and n is the number of points. Partial differentiation with respect to the coefficients yields m + 1 linear equations in m + 1 unknowns which can be solved for the coefficients.

In this project, it was noted that the cumulative penetration depth as a function of the drop number had the form $CD = A\, n^r$. This can be put into a linear from as follows

$$\ln CD = \ln A + r \ln n$$

In this case, ln CD is the dependent variable and ln n is the independent variable. A linear regression analysis was done on the transformed sets of data and a value of r for each set was obtained.

Using the average value of r, regression analysis was used to obtain A's for each curve.

The relationship between the A's and the penetrometer readings $P_{1,2,3}$ seemed to be a reciprocal function, and the following equation was assumed

$$A = a_o + \frac{a_1}{P_1} + \frac{a_2}{P_2} + \frac{a_3}{P_3}$$

A regression program was used to calculate the values of the a's. In regression analysis, the equation with all the independent variables might not be as good a predictor equation as one which uses only part of the independent variables. The criteria which is most often used is to take the predictor equation which minimizes the standard deviation of the dependent variable about the regression line. Using the regression equation, the predicted value will be within one standard deviation of the true value approximately 66% of the time.

APPENDIX C

FINAL EXPERIMENTAL SET DATA

1. TEST SERIES L
LARGE BOX/LARGE DEVICE

1.1 Test 1 L: Soil—Sifted Moist Sand

P_1 = 15.5 lbs
P_2 = 11.7 lbs
P_3 = 23.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	2.63
2	3.87
3	4.86
4	5.68
5	6.41
6	7.13
7	7.78
8	8.39
9	8.99
10	9.53

1.2 Test 2 L: Soil—Saturated Sand

P_1 = 36.0 lbs
P_2 = 21.0 lbs
P_3 = 41.2 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.53
2	.97
3	1.28
4	1.62
5	1.93
6	2.33
7	2.55
8	2.84
9	3.14
10	3.43
11	3.68

12	3.93
13	4.20
14	4.43
15	4.69

1.3 Test 3 L: Soil—Saturated and Then Drained Sand

P_1 = 68.5 lbs
P_2 = 47.5 lbs
P_3 = 82.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.31
2	.51
3	.69
4	.83
5	.99
6	1.16
7	1.33
8	1.48
9	1.61
10	1.77
11	1.91
12	2.03
13	2.19
14	2.32
15	2.48

1.4 Test 4 L: Soil—Sifted Loose Moist Silt

P_1 = 13.1 lbs
P_2 = 12.4 lbs
P_3 = 23.2 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	2.38
2	3.65
3	4.65

4	5.48
5	6.24
6	6.92
7	7.54
8	8.09
9	8.61
10	9.07
11	9.54
12	9.93

1.5 Test 5 L: Soil—Wet Compacted Silt

P_1 = 7.4 lbs
P_2 = 7.4 lbs
P_3 = 9.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	1.83
2	2.71
3	3.40
4	4.00
5	4.50
6	4.96
7	5.36
8	5.73
9	6.08
10	6.43
11	6.71
12	7.03
13	7.33
14	7.61
15	7.87

1.6 Test 6 L: Soil—Sifted Loose Dry Clay

P_1 = 28.5 lbs
P_2 = 16.5 lbs
P_3 = 43.2 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.90
2	1.40
3	1.80
4	2.13
5	2.45
6	2.75
7	3.04
8	3.30
9	3.55
10	3.79
11	4.03
12	4.26
13	4.48
14	4.67
15	4.90

1.7 Test 7 L: Soil—Wet Compacted Clay

$$P_1 = 44.0 \text{ lbs}$$
$$P_2 = 46.2 \text{ lbs}$$
$$P_3 = 53.0 \text{ lbs}$$

Drop Number	Cumulative Depth of Penetration (inches)
1	.62
2	1.00
3	1.28
4	1.55
5	1.80
6	2.00
7	2.21
8	2.39
9	2.54
10	2.70
11	2.84
12	2.98
13	3.12
14	3.25
15	3.38

2. TEST SERIES LS
LARGE BOX/SMALL DEVICE

2.1 Test 1 LS: Soil—Sifted Moist Sand

P_1 = 15.5 lbs
P_2 = 11.7 lbs
P_3 = 23.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.610
2	.942
3	1.247
4	1.527
5	1.760
6	---
7	---
8	---
9	---
10	---

2.2 Test 2 LS: Soil—Saturated Sand

P_1 = 36.0 lbs
P_2 = 21.0 lbs
P_3 = 41.2 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.070
2	.118
3	.168
4	.227
5	.287
6	.345
7	.403
8	.465
9	.519
10	.570
11	.617

12	.671
13	.728
14	.781
15	.829

2.3 Test 3 LS: Soil—Saturated and Then Drained Sand

P_1 = 68.5 lbs
P_2 = 47.5 lbs
P_3 = 82.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.037
2	.068
3	.090
4	.109
5	.129
6	.146
7	.170
8	.191
9	.208
10	.230
11	.249
12	.269
13	.289
14	.309
15	.334

2.4 Test 4 LS: Soil—Sifted Loose Moist Silt

P_1 = 13.1 lbs
P_2 = 12.4 lbs
P_3 = 23.2 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.378
2	.666
3	.952

4	1.188
5	1.398
6	1.576
7	1.746
8	1.897
9	2.041
10	---
11	---
12	---

2.5 Test 5 LS: Soil— Wet Compacted Silt

P_1 = 7.4 lbs
P_2 = 7.4 lbs
P_3 = 9.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.443
2	.750
3	.980
4	1.160
5	1.288
6	1.417
7	1.521
8	1.593
9	1.687
10	1.770
11	1.853
12	1.934
13	2.006
14	---
15	---

2.6 Test 6 LS: Soil—Sifted Loose Dry Clay

P_1 = 28.5 lbs
P_2 = 16.5 lbs
P_3 = 43.2 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.179
2	.306
3	.433
4	.536
5	.624
6	.711
7	.807
8	.879
9	.958
10	1.027
11	1.083
12	1.151
13	1.213
14	1.271
15	1.330

2.7 Test 7 LS: Soil—Wet Compacted Clay

P_1 = 44.0 lbs
P_2 = 46.2 lbs
P_3 = 53.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.107
2	.192
3	.270
4	.326
5	.393
6	.453
7	.514
8	.567
9	.622
10	.670
11	.717
12	.765
13	.812
14	.855
15	.902

3. TEST SERIES S
SMALL BOX/SMALL DEVICE

3.1 Test 1 S: Soil—Sifted Loose Dry Sand

P_1 = 17.4 lbs
P_2 = 14.5 lbs
P_3 = 29.5 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.175
2	.341
3	.540
4	.656
5	.741
6	.821
7	.896
8	.966
9	1.039
10	1.103
11	1.168
12	1.210
13	1.252
14	1.296
15	1.346

3.2 Test 2 S: Soil—Saturated Sand

P_1 = 8.4 lbs
P_2 = 7.0 lbs
P_3 = 17.2 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.064
2	.120
3	.184
4	.239
5	.304
6	.364

7	.426
8	.485
9	.550
10	.610
11	.672
12	.731
13	.793
14	.853
15	.912

3.3 Test 3 S: Soil— Saturated Then Drained Sand

$P_1 = 57.5$ lbs
$P_2 = 35.3$ lbs
$P_3 = 74.6$ lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.080
2	.136
3	.197
4	.238
5	.289
6	.329
7	.366
8	.411
9	.452
10	.482
11	.517
12	.557
13	.605
14	.626
15	.658

3.4 Test 4 S: Soil—Sifted Loose Dry Silt

$P_1 = 19.2$ lbs
$P_2 = 15.5$ lbs
$P_3 = 38.5$ lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.125
2	.216
3	.300
4	.375
5	.459
6	.535
7	.611
8	.693
9	.748
10	.805
11	.861
12	.924
13	.985
14	1.047
15	1.100

3.5 Test 5 S: Soil—Sifted Loose Dry Clay

P_1 = 26.3 lbs
P_2 = 17.0 lbs
P_3 = 57.0 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.130
2	.208
3	.269
4	.329
5	.392
6	.451
7	.515
8	.575
9	.643
10	.655
11	.703
12	.766
13	.819
14	.873
15	.927

3.6 Test 6 S: Soil—Compacted Wet Clay

P_1 = 6.70 lbs
P_2 = 7.33 lbs
P_3 = 6.85 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.539
2	.877
3	1.162
4	1.385
5	1.593
6	1.782

3.7 Test 7 S: Soil—Compacted Wet Silt

P_1 = 19.0 lbs
P_2 = 14.2 lbs
P_3 = 19.6 lbs

Drop Number	Cumulative Depth of Penetration (inches)
1	.188
2	.333
3	.470
4	.590
5	.710
6	.816
7	.923
8	1.015
9	1.105
10	1.190
11	1.262
12	1.343
13	1.416
14	1.485
15	1.555

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